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APPLICATION OF THE GLOBAL POSITIONING SYSTEM (GPS) TO THE AEROSAT TEST AND EVALUATION PROGRAM

T. L. Edwards

May 1976

Final Report

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16. Abstract

This report presents the results of a study conducted to determine the application of the Global Positioning System (GPS) to the AEROSAT Test and Evaluation Program. A summary of the GPS program elements, signal structure, navigation technique, and receiver operation is given. Operational concepts and representative options are presented which use GPS in conjunction with AEROSAT to provide a surveillance function for oceanic air traffic control. Selected options may be evaluated as part of the AEROSAT Program to assess the role of GPS in an operational oceanic air traffic control system.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

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1. INTRODUCTION

The NAVSTAR Global Positioning System (GPS) is a joint armed services program that will be developed over the next ten years to provide suitably equipped users with three-dimensional position and velocity, and system time on a worldwide basis. GPS represents a "resource" which may be used by the FAA to provide the surveillance function for oceanic air traffic control for an operational AEROSAT system. This report presents operational concepts and representative options which may be evaluated as a part of the AEROSAT Test and Evaluation Program. This evaluation will provide operational experience and data which may be used to assess the role of GPS in an operational AEROSAT system.

Section 2 presents a summary of the GPS program, including descriptions of the space, ground, and user equipment segments. Particular emphasis is placed on the Phase I user equipment which will be used for system concept and cost evaluation in Phase I testing. A functional description of three receiver classes which represent a range of operational GPS receivers is given. In addition, the performance requirements, physical characteristics, and software requirements of these receiver classes are presented.

Section 3 describes the GPS signal structure including RF characteristics, navigation code design and generation, and system data format.

Section 4 describes the GPS navigation technique which is employed to convert processed GPS signal measurements into navigational data.

Section 5 presents a description of a generic GPS receiver operating in the acquisition and tracking modes to illustrate receiver design concepts. A typical implementation of this design concept is given. The hardware requirements of this implementation are described and the characteristics of the major receiver components are given.

Section 6 discusses the operational concepts which may be employed to use GPS in the AEROSAT program. Three options are presented which embody these operational concepts and represent varying degrees of integration of GPS user equipment and AEROSAT avionics. The impact of these options on the AEROSAT avionics is also discussed in this section.

Section 7 presents the GPS system performance for Phase II and III operations. The User Equivalent Ranging Error is defined and the range measurement error sources are described. The geometric performance of the Phase II and III systems is presented in terms of satellite coverage maps and Geometrical Dilution of Precision data.

Section 8 gives a summary of the report and presents recommendations for the use of GPS in the AEROSAT Test and Evaluation Program.

2. GPS PROGRAM SUMMARY

The NAVSTAR Global Positioning System (GPS) is a satellite-based navigation system that will provide worldwide three-dimensional position, velocity, and time to users equipped with GPS receivers. It is a joint armed services program designed to meet the varied navigation requirements of all branches of the military as well as the U.S. Defense Mapping Agency. GPS provides a means for reversing the trend within the Department of Defense of proliferation of positioning and navigation equipment and systems. These payoffs are potentially available to the civil community.

The system will be developed over the next ten years in a three-phase evolutionary program that will lead to a global operational system of 24 satellites. The GPS program schedule is shown in Figure 1. The GPS system consists of three segments: a space segment, a ground segment, and a user equipment segment which are described in the following sections.

2.1 SPACE SEGMENT

The space segment for Phase I consists of six satellites. The first satellite will be a Navy navigation technology satellite (NTS-2) to be launched in 1976. In 1977, five navigation development satellites (NDS) built by Rockwell International will be launched. The six satellites will be placed in orbits with orbital periods of one half a sideral day ("twelve hour orbit"). The satellites will be deployed in two orbit planes and phased to rendezvous over the test range at Yuma, Arizona, to allow daily testing of the system over the continental United States. The Phase I development and tests will validate projected GPS costs and provide a firm basis for proceeding into the next phase.

The navigation subsystem of the navigation development satellites, shown in Figure 2, consists of the following major assembles: Pseudo

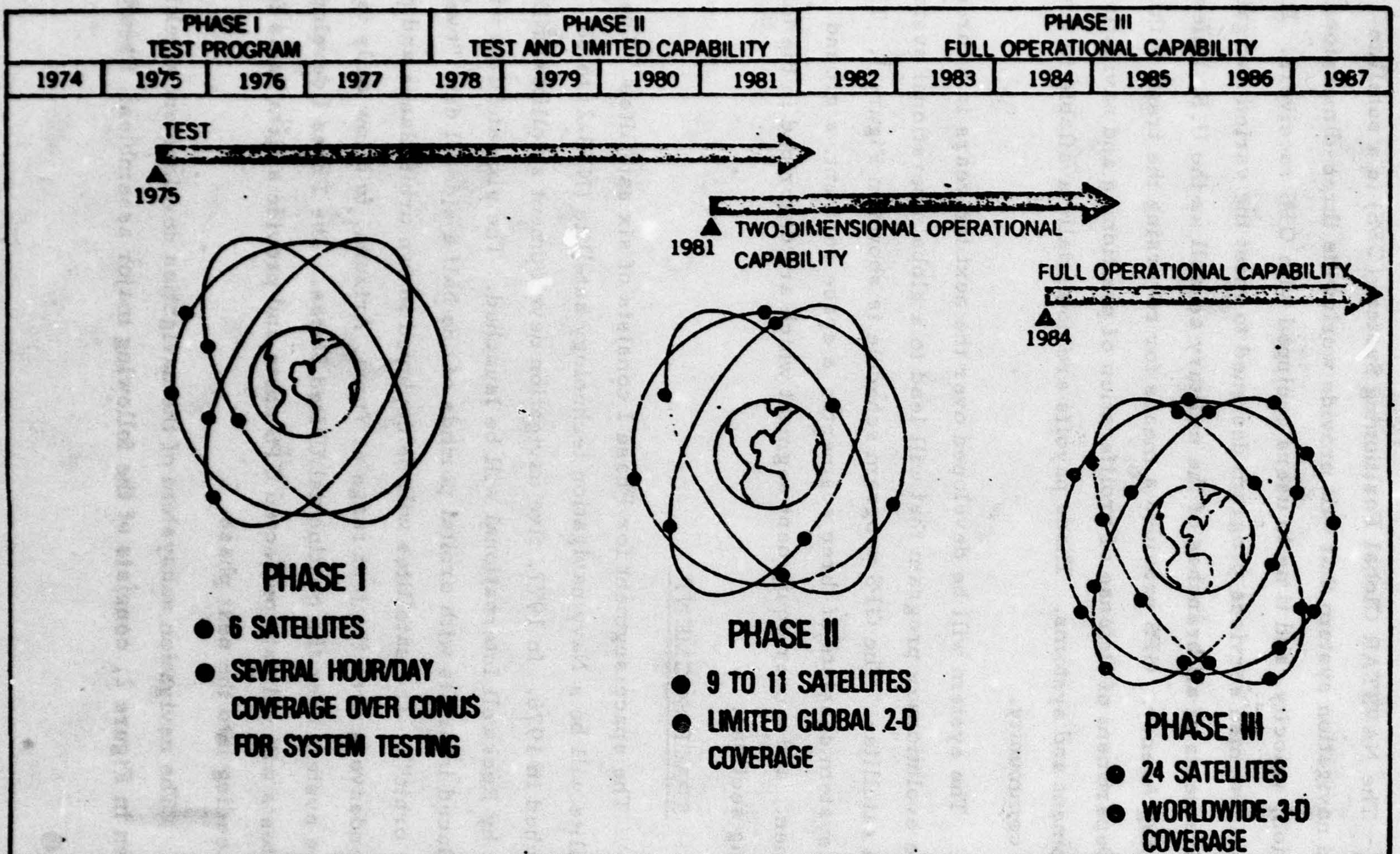
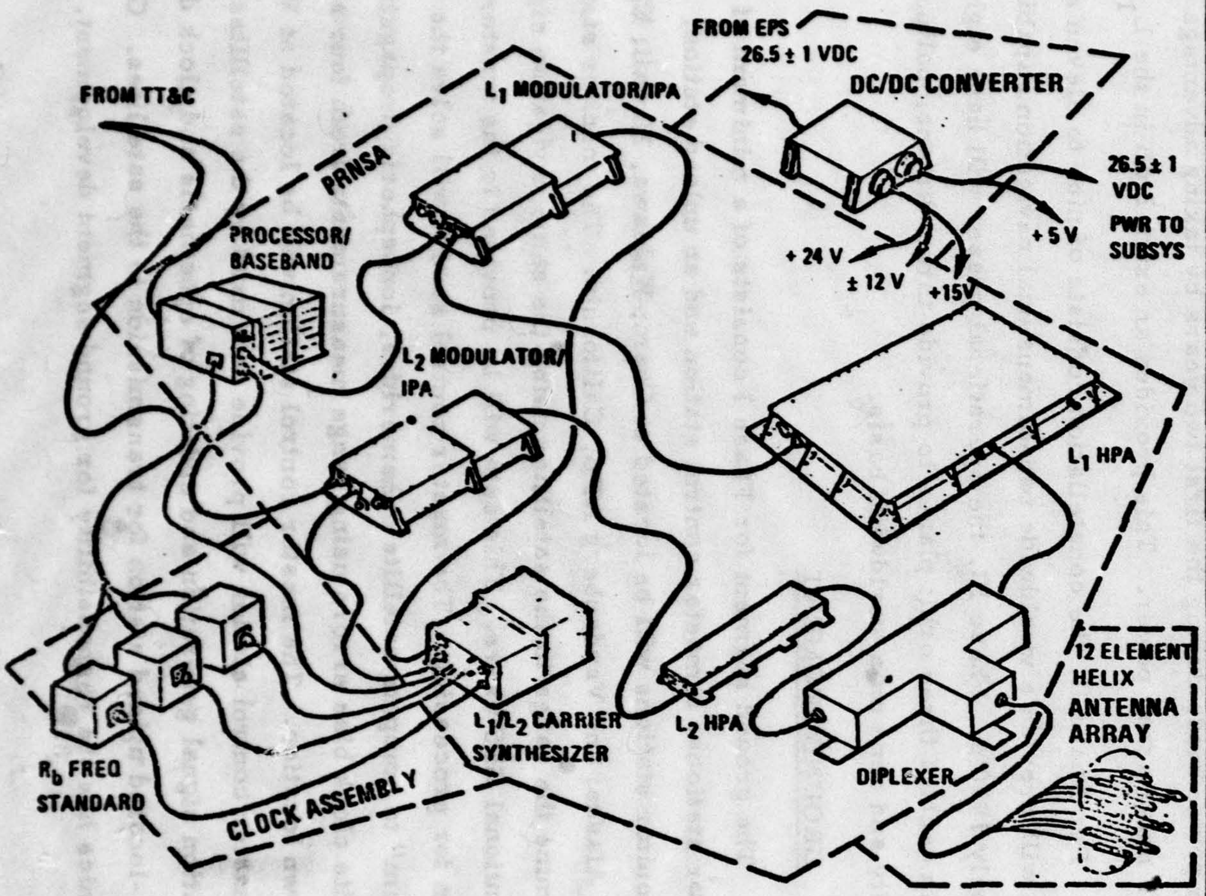


FIGURE 1. GPS PROGRAM SCHEDULE



CHARACTERISTICS		
• EIRP (FOR 5° USER EVALUATION ANGLE)		
L_1:	NORMAL MODE	
	P SIGNAL	+24.2 dBW
	C/A SIGNAL	+26.8 dBW
L_1:	HIGH POWER MODE	
	P SIGNAL	+24.2 dBW
	C/A SIGNAL	+28.8 dBW
L_2:	P SIGNAL	+19.5 dBW
	C/A SIGNAL	+19.1 dBW
• GROUP DELAY VARIATION: 3 ns		
• DIFF GROUP DELAY (L_1-L_2): 3 ns NORMAL		
5 ns ECLIPSE		
CORRELATION LOSS: 0.6 dB		
NAV PROCESSOR		
• DATA INPUT 10^3 BITS/SEC (THRU PUT)		
• STORAGE CAPACITY: 96 K BITS		
• DATA OUTPUT: 50 BITS/SEC		
CLOCK ASSEMBLY		
• RUBIDIUM ATOMIC FREQ STD (3)		
• FREQ: 10.23 MHz NOMINAL		
• STABILITY: 1×10^{-12} f/f AT 1 DAY		
ANTENNA ASSEMBLY		
• SHAPED BEAM		
• POLARIZATION: RHCP		
• GAIN (AT 14.3° OFF AXIS)		
L_1:	+13.7 dB	
L_2:	+11.3 dB	
• AXIAL RATIO		
L_1:	0.7 dB (MAX)	
L_2:	2.0 dB (MAX)	

FIGURE 2. GPS SATELLITE NAVIGATION SYSTEM

Random Noise Signal Assembly (PRNSA), DC/DC converter, clock assembly and antenna assembly. The navigation system provides an L-band carrier, L_1, modulated by a composite waveform made up a precision, P, signal and a clear/acquisition, C/A, signal. The system also provides a second L-band carrier, L_2, modulated by either the P or C/A signal. The signal structure will be discussed in greater detail in the next section. The antenna assembly is a 12-element helix array which produces a shaped beam to equalize the power received on the ground. The system can be operated in a high power mode during the first two years by taking advantage of the excess solar array power. This provides an extra 2 dB in the L_1 C/A signal.

For Phase II, the constellation consists of nine to eleven satellites, which will provide a worldwide two-dimensional navigation capability in the early 1980's. Phase III, the operational phase, will have eight satellites in each of three orbit planes to provide three-dimensional position, velocity and time on a worldwide basis.

2.2 GROUND SEGMENT

The ground segment for Phase I consists of a minimum of four monitor stations, a master control station and an upload station. Currently, the monitor stations will be located at Guam; Wahiawa, Hawaii; Elmendorf AFB, Alaska; and Vandenberg AFB, California. The monitor stations determine the range to the satellites using the same navigation signals as conventional GPS users. This data will be provided to the master control station for processing. The master control station will solve the "inverse GPS problem" to compute satellite ephemerides, ionospheric propagation and satellite clock bias errors using range measurements from four stations of known location. The master control station will be located at Vandenberg. The master control station will provide data used by the satellites for navigation signal generation and updating of ephemeris and clock data to the co-located upload station for transmission to the satellites. General Dynamics has the responsibility for ground segment development.

The ground control segment will be supported by the Air Force Satellite Control Facility (AFSCF) network. The AFSCF network will be used to provide the telemetry and command functions necessary for satellite "housekeeping" chores such as maintaining satellite health and any required orbital and attitude corrections.

2.3 USER EQUIPMENT SEGMENT

The GPS user equipment consists of, in general, an antenna, receiver, data processor, and a control/position indication. The design and performance of the user equipment is a function of the intended application. The services have initially identified several classes of user equipment with varying qualitative functional requirements. These classes are summarized in Table I as a function of accuracy, user dynamics, and jamming immunity requirements. It should be noted that these classes are only conceptual and final determination of receiver classes for the operational system will be the result of program evolution and Phase I results.

To limit the number of receiver classes for Phase I testing, a smaller set of receiver classes will be used for concept validation. There will be essentially three generic types of receivers developed for Phase I which differ primarily in the number of signals processed simultaneously and the codes (C/A and/or P) used. The qualitative characteristics of these three types are summarized in Table II.

2.3.1 PHASE I USER EQUIPMENT DESCRIPTION

User equipment for GPS Phase I testing is being developed primarily by Magnavox and Texas Instruments. Magnavox is developing three classes of receivers which are classified as type X, Y and Z. Texas Instruments is developing a high dynamics receiver, which is functionally similar to the X-receiver, and a manpack receiver. In addition, Collins

TABLE I

GPS USER EQUIPMENT CLASSES

CLASS	TYPICAL USER	ACCURACY	USER DYNAMICS	JAMMING IMMUNITY
A	Strategic	High	Medium	High
B	Tactical	High	High	Medium
C	Low Cost	Medium	Medium	Low
D	Surface (Mobile)	High	Low	High
E	Surface (Troops)	High	Low	High
F	Submarines	High	Low	Medium

TABLE II

PHASE I GENERIC RECEIVER TYPES

TYPE OF PROCESSING	NO. OF SIGNALS TRACKED SIMULTANEOUSLY	FREQUENCIES	CODES	USER DYNAMICS	ACCURACY
Continuous	≥ 4	L_1 & L_2	C/A & P	High	High
Sequential	≥ 1	L_1 & L_2	C/A & P	Medium	High
Sequential	≥ 1	L_1	C/A	Medium	Medium

Radio is developing a high anti-jam receiver under a program sponsored by the Air Force Avionics Laboratory. This receiver is a longer range development aimed at demonstrating maximum resistance to jamming by a receiver integrated with an aircraft's inertial navigation system. Brief functional descriptions of the X, Y, and Z class receivers are given below to illustrate the salient differences between the receiver types being developed for Phase I.

The X-receiver, shown in Figure 3, is capable of accepting two L_1/L_2 GPS RF inputs from two independent antenna assemblies. The major operating modes consist of search and track. Prior to, and during the search mode, aiding information such as user position, dynamics and time, along with satellite ephemerides is entered into the processor via the control display unit and/or other data processor interfaces. The processed information supplied to the receiver from the data processor is utilized to search for four satellite signals in either the normal- or direct-acquisition modes. In the normal-acquisition mode, the receiver first acquires the C/A code and then acquires the P code. In the direct-acquisition mode, the receiver directly acquires the P code. During the track mode, the X-receiver has the capability to simultaneously track any 4-of-32 NAVSTAR GPS signals for any combination of P and C/A signals at the L_1 frequency, and P-signals at the L_2 frequency, and perform one L_1 minus L_2 differential-delay ionospheric measurements. Aiding information received from the data processor during the track mode is utilized to optimize receiver performance. During track, the X-receiver demodulates navigation data and performs error detection, measures pseudorange, delta-range, and ionospheric propagation delay. The data derived during the track mode is supplied to the data processor for subsequent calculation of user position, velocity, acceleration, and system-time.

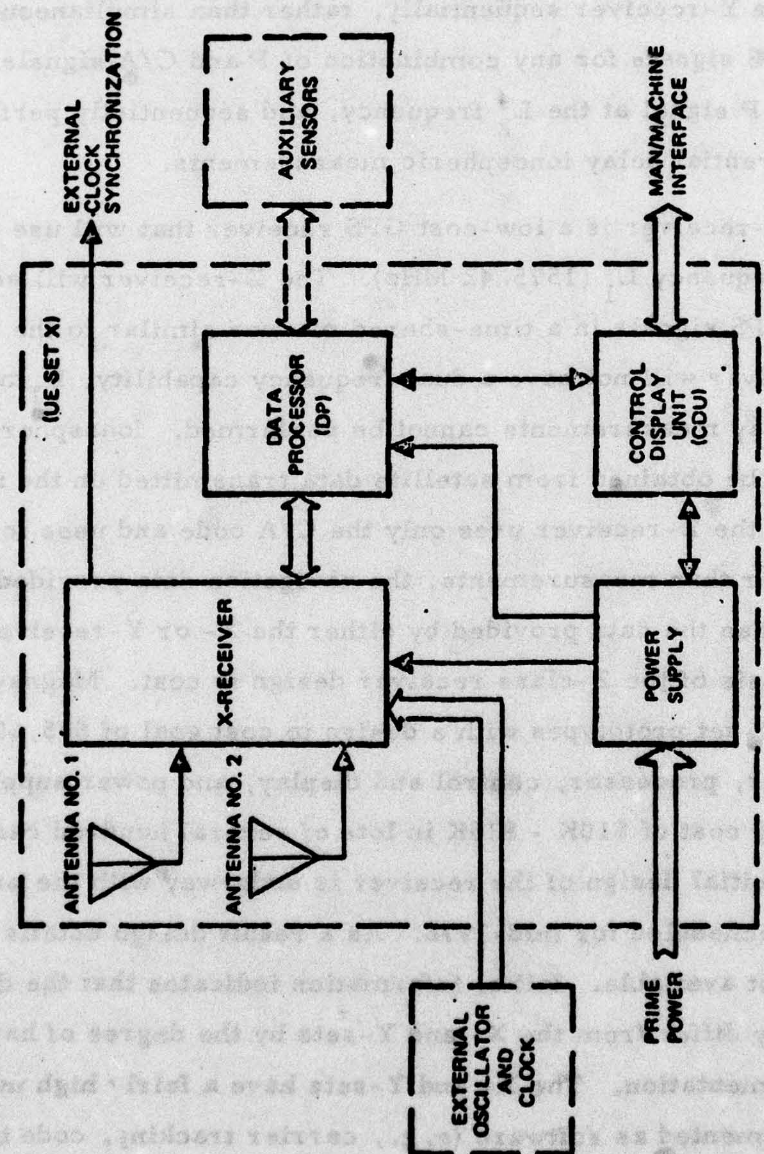


FIGURE 3. USER EQUIPMENT SET X

The Y-receiver is similar to the X-receiver with the following exceptions. The Y-receiver uses a single antenna assembly. During the track mode, the Y-receiver sequentially, rather than simultaneously, tracks any 4-of-32 GPS signals for any combination of P and C/A signals at the L_1 frequency, the P signal at the L_2 frequency, and sequentially performs L_1 minus L_2 differential delay ionospheric measurements.

The Z-receiver is a low-cost GPS receiver that will use only the C/A code on frequency L_1 (1575.42 MHz). The Z-receiver will sequentially process four GPS signals in a time-shared manner similar to the Y-receiver. Since this receiver will not have a dual frequency capability, L_1 minus L_2 ionospheric delay measurements cannot be performed. Ionospheric delay correction will be obtained from satellite data transmitted on the navigation signals. Since the Z-receiver uses only the C/A code and uses ionospheric modelling rather than measurements, the navigation data provided will be less accurate than the data provided by either the X- or Y-receiver. The primary emphasis of the Z-class receiver design is cost. Magnavox will be developing 14 Z-set prototypes with a design to cost goal of $25,000 per set including receiver, processor, control and display, and power supply. It is hoped that a recurring cost of $10K - $15K in lots of several hundred can be demonstrated. The initial design of the receiver is underway with the preliminary design review scheduled for mid-1976. As a result design details on the Z-receiver are not available. Initial information indicates that the design of the Z-receiver may differ from the X- and Y-sets by the degree of hardware vs. software implementation. The X- and Y-sets have a fairly high number of functions implemented as software (e.g., carrier tracking, code tracking, data demodulation). The Z-receiver may have some of these function implemented as hardware. Due to the emphasis on cost, the Z-receiver design will depend on hardware/software trade-offs to obtain the desired performance at a reasonable cost. In addition, unlike the X- and Y-sets, the Z-receiver will not be designed

to interface with auxiliary sensors such as inertial measurement units and air data sets for performance augmentation.

2.3.2 PHASE I USER EQUIPMENT PERFORMANCE

The navigational accuracy of the GPS X- and Y-receivers is on the order of 10 meters (1σ). Since the X receiver processes four signals simultaneously, it will provide high accuracy navigation data to high dynamic users. The Y-receiver will provide high accuracy navigation data to medium dynamics users, since it processes the signals sequentially. The Z-receiver is being designed to provide medium accuracy navigation data to medium dynamics users. The navigation accuracy of the Z-class receiver is on the order of 100 meters (1σ). The user dynamics for each set are shown in Table III. It should be noted that the navigational accuracies stated above are order-of-magnitude numbers and are for the Phase III satellite configuration. Navigational accuracy is dependent on many factors such as satellite ephemerides and propagation effects as well as receiver errors and processing errors. The performance requirements of the Phase I X-, Y-, and Z-receivers are described below. The performance of the total GPS system is described in greater detail in Section 7 of this report.

2.3.2.1 TIME-TO-FIRST FIX

The Time-To-First Fix (TTFF) is defined as the amount of time required to produce a single point navigation solution from the start of the acquisition mode. The TTFF's for the X-, Y-, and Z receivers and the conditions under which the requirements are to be met are shown in Table IV for both the normal and direct acquisition modes. The 3σ range measurement errors, including ionospheric and tropospheric modeling/measurement errors and multipath errors, used to compute the

TABLE III

USER DYNAMICS FOR X-, Y-, AND Z RECEIVERS

(FROM REFERENCE 1)

Dynamics \ Set	X	Y	Z
Velocity (m/sec)	0-900	0-600	0-600
Acceleration (m/sec^2)	0-50	0-20	0-20
Jerk (m/sec^3)	100	100	50

TABLE IV

TTFF AND SIMULTANEOUS CONDITIONS

(FROM REFERENCE 1)

a) NORMAL ACQUISITION

Set	X		Y		Z	
J/S Conditions	Poor	Good	Poor	Good	Poor	Good
TTFF (sec)	180	80	300	225	300	200
J/S condition* (dB)	24.5	≤19	25.5	≤19	25.5	≤19
Probability of success (%)	90	90	90	90	90	90
**Position Uncertainty (Km)(1σ)	650	650	175	175	175	175
**Velocity Uncertainty (m/sec)(1σ)	150	150	30	30	30	30
Max. Vehicle Acceleration (m/sec^2)	10	10	10	10	10	10
Max. Vehicle Jerk (m/sec^3)	100	100	100	100	50	50

*Receiver Input Signal Level ≥ -163 dBw but not to exceed -130 dBw. For a uniform distribution of position and velocity uncertainty, the specified J/S increases by 2 dB.

**For a Gaussian distribution.

b) DIRECT ACQUISITION

Set	X				Y			
Available Time Reference	Internal		External***		Internal		External***	
TTFF (sec)	200	100	120	100	600	250	480	250
J/S condition (dB)*	34	27	34	27	34	27	34	27
Max. Time Between Resetting Time Reference (Days)****	0.1	0.1	1	1	0.1	0.1	1	1
User Clock Uncertainty (usec)(1σ)**	10	10	10	10	10	10	10	10
Probability of Success (%)	90	90	90	90	90	90	90	90
Position Uncertainty (m) **(1σ)	9260	9260	9260	9260	9260	9260	9260	9260
Velocity Uncertainty (m/sec)**(1σ)	30	30	30	30	15	15	15	15
Max. Vehicle Acceleration (m/sec^2)	10	10	10	10	10	10	10	10
Max. Vehicle Jerk (m/sec^3)	100	100	100	100	100	100	100	100
Satellite Clock Uncertainty (usec)** (1σ)	5	5	5	5	5	5	5	5

*Receiver Input Signal Level > -163 dBw but not to exceed -130 dBw. For a uniform distribution of position and velocity uncertainty, the specified J/S increases by 4 dB.

**For a Gaussian distribution.

***Using an external time reference having a $\Delta F/F = 5 \times 10^{-11}$ (τ = 1 sec) and an aging rate a = 1×10^{-10} per month, TTFF for Sets X, and Y shall not exceed 120 sec and 480 sec respectively.

****From external standard accurate to 1 μs in GPS time or a four (4) satellite fix by the set itself.

first single point navigational fix is specified to be less than 16 meters for the X- and Y-receivers and less than 100 meters for the Z-receiver.

2.3.2.2 SIGNAL REACQUISITION

The requirements for signal reacquisition upon loss of signal are given in Table V.a. The Y- and Z-receivers perform routine signal tracking terminations since processing is done sequentially. The conditions for sequential recovery of synchronization are given in Table V.b.

2.3.2.3 JAMMING IMMUNITY

The receivers are required to perform the functions listed in Table VI under the indicated jamming signal-to-navigation signal received power (J/S) conditions. All J/S conditions are based on non-coherent CW interference.

2,3.2.4 PSEUDO RANGE AND PSEUDO RANGE RATE MEASUREMENT

The receivers are required to measure pseudo range and pseudo range rate to a accuracy which meets or exceeds the values specified in Table VII. Pseudo range is the distance equivalent of the time of propagation of the navigation signal from the satellite to the receiver and, hence, is not equivalent to the geometrical range. Pseudo range rate is a measure of the change of pseudo range over a specified integration interval.

2.3.2.5 IONOSPHERIC DELAY ERROR

The X- and Y-receivers are capable of using dual frequency measurements to determine ionospheric delay. The required measurement accuracy is better than 5 meters (1σ) under the nominal navigation signal levels and the J/S condition specified in Table VI. All receivers have the capability of compensating for ionospheric propagation signal delay by using modelling techniques and satellite data. The 1σ values of

TABLE V

REACQUISITION CONDITIONS

(FROM REFERENCE 1)

a) ABNORMAL SIGNAL LOSS

Set	X		Y		Z
Signal	P	C/A	P	C/A	C/A
Loss Period (sec)	10	10	10	10	10
Reacquisition time (sec)	10	10	10	10	10
Probability of reacquisition	.95	.95	.95	.95	.95
Position uncertainty* (m) (1σ)	305	305	305	305	305
Velocity uncertainty* (m/sec) (1σ)	15	15	15	15	15
Acceleration uncertainty* (m/sec^2) 1σ	3	3	3	3	3
Jerk uncertainties* (m/sec^3) (1σ)	10	10	10	10	10
J/S condition (dB)**	40	30	30	30	30

*For a Gaussian distribution
**Receiver Input Signal Level $\geq$ - 163 dBw but not to exceed -130 dBw.

b) NORMAL SIGNAL LOSS

Set	Y		Z
Signal	P	C/A	C/A
Probability of Synchronization Recovery (%)	99	99	99
J/S condition (dB)*	40	30	30
Vehicle Velocity (m/sec)	0-600	0-600	0-600
Vehicle Acceleration (m/sec^2)	0-10	0-10	0-10
Jerk (m/sec^3)	100	100	50

*Receiver Input Signal Level $\geq$ -163 dBw but not to exceed -130 dBw.

TABLE VI

JAMMING IMMUNITY

(FROM REFERENCE 1)

Set	Signal	****Initial Signal Acquisition	Carrier Lock	Carrier Track	*Code Track	Data Recovery Byte Reception (P=.99)	Data Recovery Bit Error Rate (10^{-5})	Ionosphere Diff. Meas.	*Seq. Sync Recovery	*HOBYT Mode Code	*HOBYT Mode Seq. Sync Recovery
X	P (J/S-dB)	34	49	43	44	41	47	44	NA	49	NA
X	C/A (J/S-dB)	24.5	39	33	34	31	37	NA	NA	39	NA
Y	P (J/S-dB)	34	49**	43**	40	41**	47	44**	40	NA	42
Y	C/A (J/S-dB)	25.5	39**	33**	30	31**	37	NA	30	NA	32
Z	C/A (J/S-dB)	25.5	30	30	30	30	30	NA	30	NA	32

*When an inertial measurement unit is used in conjunction with Sets X or Y, code tracking HOBYT and sync recovery shall be maintained for J/S conditions of at least 54 dB for the P-signal and 44 dB for the C/A-signal.

**When an inertial measurement unit is used in conjunction with Set Y. Without aiding, these values reduce to the corresponding values in the column headed "Sequential Sync Recovery."

***Receiver Input Signal Level ≥ -163 dBw but not to exceed -130 dBw.

****For a uniform distribution of position and velocity uncertainty, the specified J/S increases by 4 dB for the P-signal and 2 dB for the C/A signal.

TABLE VII

PSEUDO RANGE AND PSEUDO RANGE-RATE MEASUREMENT ACCURACY

(FROM REFERENCE 1)

Set / Error (1σ level)	X		Y		Z
	P Signal	C/A Signal	P Signal	C/A Signal	C/A Signal
Range (meters)	1.5	15	1.5	15	15
*Range Rate (meters)	.006	.006	.006	.006	.006

*Integration Time ≥ 0.1 sec.

ranging errors resulting from the modelling techniques shall be no greater than 6 meters for Sets X and Y, and 15 meters for Set Z.

2.3.2.6 RANGING AND RANGE RATE ERROR

The total 3σ range measurement errors including dual frequency ionospheric correction, tropospheric correction, and multipath errors are specified to be less than 16 meters for either Sets X or Y. The error in range measurement due to biases between receiver channels, receiver channel delay calibration, and systematic receiver channel delay variation is specified to be less than 1 meter. The total 3σ range measurement error for Set Z shall be less than 100 meters.

Range rate is a measure of the change in range over a defined interval of time, T, in which the interval T immediately precedes the demand for the measurement. The total 1σ range rate measurement errors are required to be less than 0.006 meter for $T \geq 0.1$ second.

These requirements apply under nominal signal levels, J/S conditions specified in Table VI, and the dynamics in Table III.

2.3.2.7 EQUIPMENT STABILIZATION PERIOD

The Equipment Stabilization Period (ESP) is the time from equipment turn-on until the 1σ pseudo range and pseudo range rate measurement accuracies given in Table VII are achieved. The requirements on ESP as a function of ambient temperature for the receivers is shown in Figure 4. The "poor" and "good" J/S conditions refer to the levels given in Table IV.

2.3.3 PHASE I USER EQUIPMENT PHYSICAL CHARACTERISTICS

The design goals for the Phase I user equipments Sets X, Y, and Z are given in Table VIII. All sets are designed to operate on 115 VAC, 400 Hz, three phase, as well as +28 VDC, Category C. Sets X and Y are required to have backup power to maintain set operation for not less than 7 seconds in the event of prime power interrupt. In addition, battery

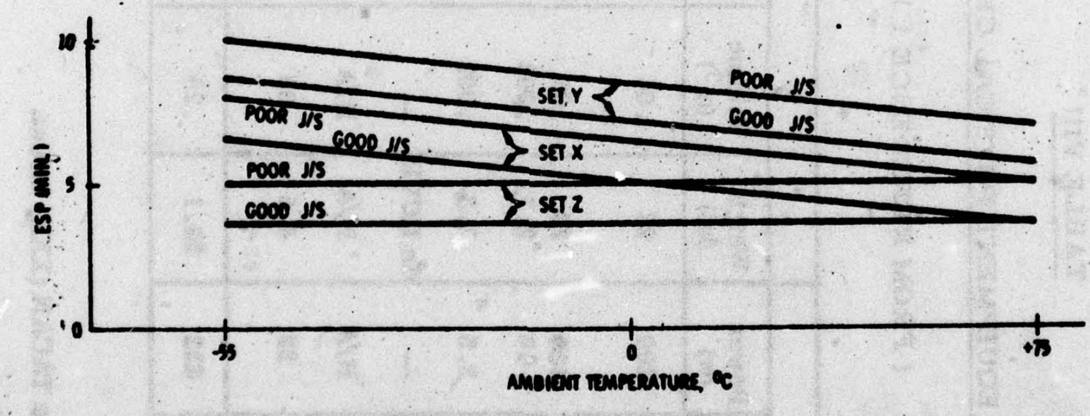


FIGURE 4. ESP VS AMBIENT TEMPERATURE

(FROM REFERENCE 1)

TABLE VIII

PHASE I USER EQUIPMENT PHYSICAL CHARACTERISTICS

(FROM REFERENCE 1)

	X			Y			Z*		
	Weight (kg)	Volume (m^3)	Power (w)	Weight (kg)	Volume (m^3)	Power (w)	Weight (kg)	Volume (m^3)	Power (w)
Receiver	27	.04	200	23	.04	120	11	.01	120
Data Processor	20	.06	400	20	.06	400	1.4+	.002+	
CDU	2.3	.002	10	2.3	.002	10	2.3	.002	10
Antenna Preamp	2.3	.002	2.5	2.3	.002	2.5	2.3	.001	1
Power Supply	In RCVR	--	--	In RCVR	--	--	In RCVR	--	--
Interfaces	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Other Eng. Control Display	4.5	.09	20	4.5	.09	20	4.5	.09	20
Total	56.1	.20	632	52.1	.20	552	22.5	.11	151

*Airborne Configuration, which fits the TACAN (XXX) mount.

+Included in receiver weight or volume.

power is required in the Set X or Y receiver to preserve the data required for direct acquisition for not less than 30 minutes in the event of prime power interrupt.

2.3.4 PHASE I USER EQUIPMENT SOFTWARE FUNCTIONS

The software of the Sets X, Y, and Z will be designed to perform the following functions:

(1) Executive control
(2) Software initialization
(3) GPS satellite selection
(4) Auxiliary sensor monitor and control (X and Y only)
(5) Receiver measurement processing
(6) Navigation
(7) Control/display
(8) Self-test

The navigation function (item 6 above) refers to the processing of measurement data to optimally estimate user position, velocity, and system time. In addition, application software will also be provided to allow waypoint navigation. Up to eight waypoint coordinates are allowed. By inputting the desired track to the selected waypoint, the following items can be computed and displayed:

(1) Present position in latitude and longitude
(2) Position of selected waypoint in latitude and longitude
(3) Bearing to selected waypoint with reference to true North
(4) Distance to selected waypoint and time-to-go to current waypoint
(5) Ground Speed
(6) Ground track with respect to true North
(7) Cross track error
(8) Time-of-day

By inputting magnetic heading, magnetic variation, and true air speed, the applications software will compute the following:

(1) Bearing to selected waypoint relative to magnetic North
(2) Drift angle
(3) Ground track relative to magnetic North
(4) Wind speed and wind direction
(5) North and East velocity

By inputting the desired altitude for each waypoint and vertical approach angle for current waypoint, the applications software will compute the following:

(1) Present altitude
(2) Vertical velocity
(3) Vertical error

In addition, the application software will determine the number of satellites being tracked and the 3σ uncertainty in navigation performance to provide information on data quality to the user.

3. GPS SIGNAL STRUCTURE

3.1 RF CHARACTERISTICS

The GPS satellites transmit navigation signals on two L-band carriers. The primary navigation signals are transmitted on carrier L_1 which is at 1575.42 MHz. The second carrier, L_2, is at 1227.6 MHz. The L_1 carrier is bi-phase shift key (BPSK) modulated by two pseudo random sequences; a precision (P) navigation signal, and a clear/acquisition (C/A) navigation signal. The P and C/A carrier components are in phase quadrature. The L_2 carrier is BPSK modulated by the same P or C/A signal which is used to modulate L_1. Note that L_2 does not contain the P and C/A signals simultaneously. The transmission of the P or C/A navigation signal is selectable by ground command. The primary use of the L_2 signal is to obtain a correction for ionospheric propagation delay by dual frequency measurements. In addition, the L_2 signal provides a backup signal in the event of L_1 failure.

The minimum received signal levels on the earth's surface when the satellite is above an elevation of 5 degrees are given in Table IX. The received levels are specified relative to the output of a 3dB linearly polarized receiving antenna. The transmitted signals are Right-Hand Circularly Polarized (RHCP) so, in effect, the levels specified in Table IX are relative to a 0 dB gain RHCP receiving antenna. The C/A navigation signal on L_1 may be operated in a high power mode by taking advantage of the excess solar array power during the first 2 years to provide and extra 2dB in the L_1 C/A signal.

The P navigation signal is the modulo 2 sum of the P code and system data. The C/A navigation signal is the modulo 2 sum of the C/A code and the same system data. The primary military use of the C/A signal is to aid in the acquisition of the P signal. The P code, C/A code, and system data are described in the following sections.

TABLE IX

MINIMUM RECEIVED SIGNAL LEVELS

CARRIER	CODE	
	C/A	P
L_1	- 160 dBW Normal Mode - 158 dBW High Power Mode	- 163 dBW
L_2	- 166 dBW	- 166 dBW

Note: All levels relative to output of 3dB linearly polarized antenna.

3.2 P CODE

The P code is a pseudo noise (PN) sequence with a chipping rate of 10.23 MBps. The P code is generated by the modulo 2 sum of two PN codes $X1(t)$ and $X2(t+n_i T)$, where T equals the period of one P-code chip. The composite code $X1(t) \oplus X2(t+n_i T)$ is selected to have a period of approximately 267 days to accommodate 32 different initial code phases, each displaced by a minimum of seven days. Each satellite delays the X2 code by a unique amount (n_i chips) to give each of 32 satellites a unique seven day portion of the 267 day code. At the end of each seven day week the code generators are reset to their initial state.

The X1 code is itself generated by the modulo 2 sum of the output of two 12-stage registers, X1A and X1B, which have been short cycled to 4092 and 4093 chips, respectively. When 3750 X1A short cycles have been counted, both the X1A and X1B generators are reset and the X1 epoch is generated. The X1 epoch occurs each 1.5 seconds, after 15,345,000 chips of the X1 pattern.

The X2 code is similarly generated by the modulo 2 sum of the output of two 12-stage registers, X2A and X2B, which have been short cycled to 4092 and 4093 chips, respectively. When 3750 X2A short cycles have been counted, both X2A and X2B are held in their final state for 37 more of the 10.23 MHz clock pulses before beginning again. The resulting period of X2 is 15,345,037 chips. The long composite code is obtained by the modulo 2 sum of the X1 and X2 codes which have nearly equal periods.

3.3 C/A CODE

The C/A codes are Gold codes of length 1023 bits at a chipping rate of 1.023 Mbps. As a result the C/A codes are 1 millisecond in length. The epochs of the Gold codes are synchronized with the X1 epoch

of the P code. Each satellite is assigned a unique C/A code to provide code division multiplex accessing of the satellites.

The C/A code itself is the modulo 2 sum of two 1023 bit linear sequences G1 and $G2_i$ generated by 10-stage shift registers. The generation of the C/A codes is illustrated in Figure 5. The unique C/A codes are selected by the modulo 2 addition of the contents of a pair of stages of the G2 shift register to form $G2_i$ which is then modulo 2 added to G1.

Gold codes are used to minimize the cross-correlation between codes from different satellites and, hence, provide good discrimination between satellites. The un-normalized correlation properties of codes in a Gold code family can be shown to be the following:

<u>for n odd</u>

$$C_{ij}(\tau) = \begin{cases} -1 \\ -1 + 2^{\frac{n+1}{2}} \\ -1 - 2^{\frac{n+1}{2}} \end{cases}$$

$$R_i(\tau) = \begin{cases} L & \text{for } \tau = 0 \\ C_{ij}(\tau) & \text{for } \tau \neq 0 \end{cases}$$

<u>for n even and not divisible by 4</u>

$$C_{ij}(\tau) = \begin{cases} -1 \\ -1 + 2^{\frac{n+2}{2}} \\ -1 - 2^{\frac{n+2}{2}} \end{cases}$$

$$R_i(\tau) = \begin{cases} L & \text{for } \tau = 0 \\ C_{ij}(\tau) & \text{for } \tau \neq 0 \end{cases}$$

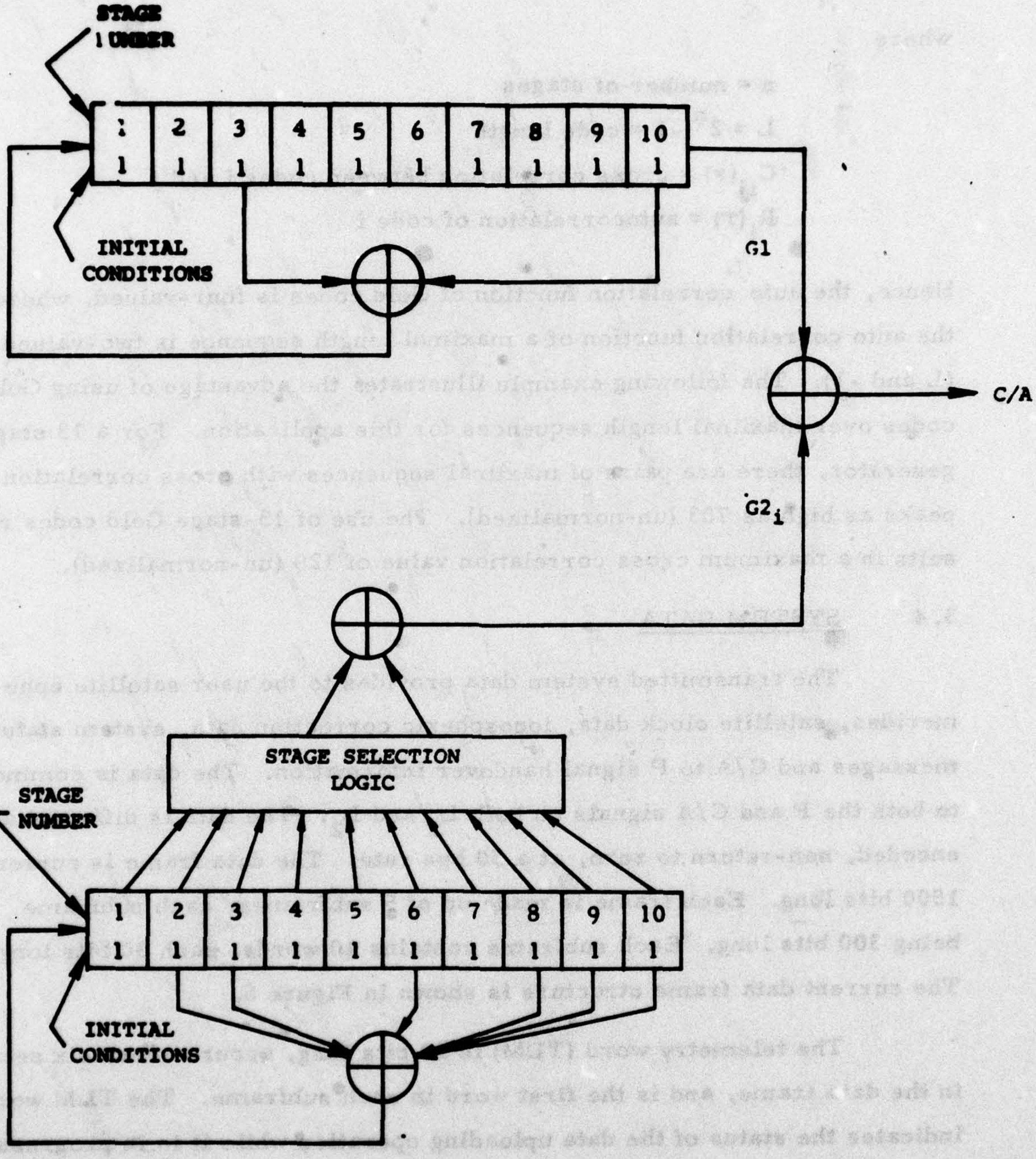


FIGURE 5. C/A CODE GENERATION

where

n = number of stages

$L = 2^n - 1$ = code length

$C_{ij}(\tau)$ = cross correlation between codes i and j

$R_i(\tau)$ = autocorrelation of code i

Hence, the auto correlation function of Gold codes is four-valued, whereas the auto correlation function of a maximal length sequence is two-valued (L and -1). The following example illustrates the advantage of using Gold codes over maximal length sequences for this application. For a 13 stage generator, there are pairs of maximal sequences with cross correlation peaks as high as 703 (un-normalized). The use of 13-stage Gold codes results in a maximum cross correlation value of 129 (un-normalized).

3.4 SYSTEM DATA

The transmitted system data provides to the user satellite ephemerides, satellite clock data, ionospheric correction data, system status messages and C/A to P signal handover information. The data is common to both the P and C/A signals on both L_1 and L_2. The data is differentially encoded, non-return to zero, at a 50 bps rate. The data frame is currently 1500 bits long. Each frame is made up of 5 subframes, each subframe being 300 bits long. Each subframe contains 10 words, each 30 bits long. The current data frame structure is shown in Figure 6.

The telemetry word (TLM) is 30 bits long, occurs every six seconds in the data frame, and is the first word in each subframe. The TLM word indicates the status of the data uploading operation while it is in progress. The handover word (HOW) is also 30 bits long and is the second word in each subframe immediately following the TLM word. The HOW contains the "Z-count" which is related to the number of X1 code epochs that have occurred since the end of the previous week. This information is used to aid in the acquisition of the P code.

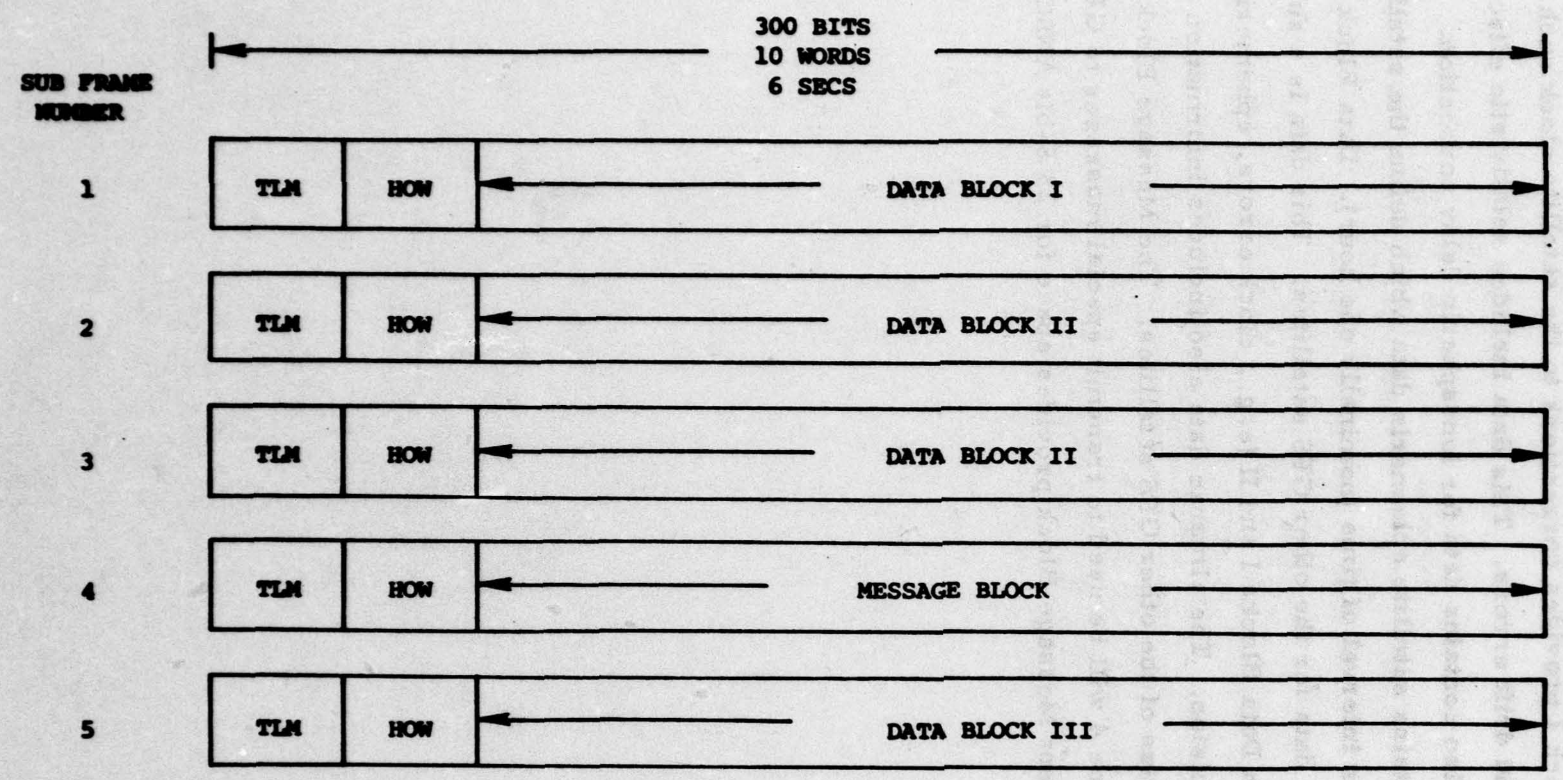


FIGURE 6. SYSTEM DATA FORMAT

Data Block I provides corrections to the satellite clock such as clock offset and drift errors. This data includes relativistic effects. This data block also contains data for ionospheric delay correction. Data Block II contains satellite ephemeris data which define the satellite orbit for a certain interval of time (nominally one hour). Data Block III contains almanac data for the other GPS satellites. This data is a subset of the parameters in Data Blocks I and II (e.g., clock errors, ephemerides) with reduced precision. The almanac data also includes information about the health and status of the other GPS satellites. The Message Block which is part of subframe 4 will be used to transmit special messages to GPS users. The current Message Block provides space for 23 8-bit ANSCII characters.

4. GPS NAVIGATION TECHNIQUE

To determine position and velocity, a user cross-correlates pseudorandom codes which are locally generated in the receiver with the code-division multiplexed navigation signals transmitted from the satellites. The relative phase or equivalent time displacement between the local code and the incoming signals is measured allowing determination of the relative range. In general, the user is not synchronized to system time, so that the range measurements obtained are not equivalent to the geometrical ranges to the satellites. In addition the range measurements are corrupted by satellite clock errors, propagation effects, and errors in the measurement process. As a result the measurements are termed pseudoranges. Each receiver pseudorange measurement can be expressed as:

$$S_n = |\vec{R}_n| + c(b_u - b_n) + \Delta L_n + \delta_n$$

where

S_n	=	pseudorange measurement to n th satellite
$\lvert\vec{R}\rvert$	=	geometric range to n th satellite
c	=	speed of light
b_u	=	user clock error
b_n	=	clock error of n th satellite
ΔL_n	=	propagation link errors
δ_n	=	receiver measurement error

The system data which is transmitted on the navigation signals will provide estimates of satellite clock errors and ionospheric effects. For receiver configurations with a dual frequency capability, the ionospheric delay may be measured. Propagation effects which are not frequency dependent may

be modelled to provide estimates of their effects. Using the satellite data and modelling the pseudorange measurements may be corrected by on board processing. The resulting corrected pseudoranges, ρ_n, may be expressed as:

$$\rho_n = |\vec{R}_n| + cb_u + \epsilon_n$$

where

ρ_n = pseudorange corrected by estimated error effects

ϵ_n = error due to incomplete modelling or measurement errors.

If it is assumed that the measurements and modelling techniques are sufficiently accurate, then

$$\rho_n = |\vec{R}_n| + cb_u$$

The user clock error, b_u, is unknown and will be determined in the solution of the final equations along with user position.

The geometry between the user and the satellites may be written as:

$$\vec{R}_n = \vec{P} - \vec{E}_n$$

where

$\vec{R}_n$ = vector from n th satellite to the user

$\vec{P}$ = user position vector from center of earth

$\vec{E}_n$ = satellite position vector from center of earth

The geometrical range from user to the satellite is, therefore

$$|\vec{R}_n| = |\vec{P} - \vec{E}_n|$$

The data transmitted on the navigation signals will provide satellite orbital data sufficient to determine the satellite position vector $\vec{E}_n$. Using the above expression and the corrected pseudorange the system to be solved is

$$|\vec{P} - \vec{E}_n| = \rho_n - cb_u$$

Expressing $\vec{P}$ and $\vec{E}$ in component from

$$\vec{P} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \qquad \vec{E}_n = \begin{bmatrix} X_n \\ Y_n \\ Z_n \end{bmatrix}.$$

the above expression becomes

$$(X - X_n)^2 + (Y - Y_n)^2 + (Z - Z_n)^2 = (\rho_n - cb_u)^2$$

There are four unknowns (X, Y, Z, b_u) so that a minimum of four satellite pseudorange measurements are required. It should be noted that the satellite position vectors $\vec{E}_n$ are functions of system time (and, hence, a function of b_u) so that, in general an iterative scheme is used to solve for user position (X, Y, Z), and user clock error which provides system time.

The formulation for velocity determination is similar to the position determination formulation. The user measures navigation signal doppler to obtain pseudorange rate and determines satellite velocities $\dot{\vec{E}}_n$ from ephemeris data. The equations in terms of the corrected pseudorange rate $\dot{\rho}_n$ to be solved are

$$|\dot{\vec{P}} - \dot{\vec{E}}_n| = \dot{\rho}_n - c\dot{b}_u \qquad n = 1,4$$

where $\qquad \dot{\vec{P}}$ = user velocity vector.

5. GPS USER EQUIPMENT OPERATION

The general function of the GPS user equipment is to receive and process GPS navigation signals and provide three dimensional position and velocity and system time to the user. Specifically, the GPS user equipment performs the following functions (Reference 1):

a) Detect and acquire the navigation signals generated by the GPS transmitters.

b) Track the acquired signals.

c) Discriminate against multipath signals.

d) Provide immunity against jamming and spoofing

e) Perform corrections for ionospheric signal delay, either by mathematical modeling or through RF signal measurement techniques.

f) Extract the data contained in the received navigation signals.

g) Accomplish the pseudo-range and pseudo-range-rate measurements as required.

h) Compute and output the user's three-dimensional position and velocity and system time in the required format.

i) For User Equipment Sets X and Y augmented with Auxiliary Sensor Sets, accept position, velocity, attitude and/or timing data from external sensors or sources for the purpose of providing refinement to the navigational solution or to increase jamming and spoofing immunity.

The above functions may be grouped into the two operating modes of the GPS user equipment: acquisition and tracking. The function of the acquisition mode is to perform item a). The tracking mode includes items b), e), f), g), and h). Here the tracking mode is taken to mean all signal tracking, measurements, and computations required to obtain navigational data. Items c), d), and i) have certain implications on equipment design and implementation and apply to both the acquisition and tracking modes.

This section will describe the acquisition and tracking modes of the GPS user equipment. The discussion will be based on a generic GPS receiver, and not on a specific receiver design. The purpose of the discussion is to indicate design concepts rather than design details. The GPS user equipment sets that are being developed are designed to evaluate system performance and costs for various classes of users. The specific requirements of any GPS equipment used in the AEROSAT Test and Evaluation Program may or may not conform to one of these designs. In general, GPS equipment used in the AEROSAT program may be of the following types: 1) "as-designed" GPS user equipment; 2) partially re-designed GPS equipment which is modified for the AEROSAT application; or, 3) totally re-designed GPS equipment to fulfill AEROSAT unique requirements. Once the application of GPS to the AEROSAT program is defined and the required performance is established, the appropriate type (as-design, re-designed, etc.) of GPS equipment may be selected and implemented.

To illustrate the hardware requirements of a typical GPS user equipment set, the major components are listed and briefly described in this section. The design and component characteristics are representative of a GPS X- or Y-set being developed by Magnavox. As will be shown, many of the receiver functions are implemented as software. The degree of software implementation for other receiver design (e.g. the Z-class receiver) may vary depending on receiver performance and cost requirements.

5.1 AQUISITION

The GPS system enables the system users to navigate in near real time by calculation of position and velocity based upon pseudorange and pseudorange-rate measurements from each of four satellites in view. A user entering the system must first determine which satellites are visible in order to start the GPS signal acquisition process. However, depending on user location and time, as many as eleven satellites may be visible for the Phase III configuration. The number of combinations

of 11 satellites taken four at a time is 330. Each combination will result in varying navigation accuracies due to the differing geometries. Hence, before the signal acquisition process is initiated the GPS receiver must first determine which set of four satellites (codes) will be used in the correlation process. This section will briefly discuss procedures for satellite selection. This discussion will illustrate one of the additional processing duties of the GPS data processor which is in addition to the normal navigational computations. After the set of four satellites is selected, the signal acquisition procedure may begin. This section will describe the signal acquisition process including a functional description of the code and carrier synchronization methods to initiate code and carrier tracking. Once the loops are tracking, pseudorange and pseudorange-rate may be measured and satellite data can be demodulated to determine the user state vector and provide navigation data.

5.1.1 SATELLITE SELECTION PROCEDURES

The user's ability to navigate depends not only on the availability of four satellites but also on the relative positions between the user and the satellites. Errors in pseudoranging are magnified and the navigation precision is diluted as a function of the user-satellite geometry. This dilution of range measurement precision is generally expressed by the performance index GDOP (Geometric Dilution of Precision). GDOP is the ratio of the position error statistics to the pseudoranging error standard deviation under the stipulation that all satellite ranging measurement errors are expressed as uncorrelated errors with equal standard deviations.

After determining the population of visible satellites based on a rough estimate of user position and time, the GPS receiver may determine the set of four satellites which minimizes GDOP. The computational process involves the evaluation of the covariance matrix of the user position and time bias errors for each combination of N visible satellites taken four at a time; i.e.,

$$\binom{N}{4} = \frac{N!}{(N-4)!\,4!}$$

As many as 11 satellites may be visible to a user which results in 330 different combinations. The determination of the optimum set of four satellites out of the possible 330 combinations can result in a lengthy computation process.

An alternate algorithm for satellite selection is based on the fact that there is an extremely high correlation between the volume of a tetrahedron formed by the four user-to-satellite unit vectors and GDOP. The minimum GDOP (corresponding to the maximum tetrahedron volume) may be established by selecting the highest satellite in the sky and the three visible satellites which maximize the volume of the tetradedron. The GDOP may be computed only for this optimum combination and displayed to the user as an indication of position determination accuracy. Implementation of this algorithm is described below.

The GPS user is required to have crude ephemerides of all satellites in the GPS system and an estimate of his position and time. With this data the user may calculate his estimated position vector and the position and velocity vectors of all GPS satellites. The user/satellite geometry is illustrated in Figure 7. The user then calculates the unit vectors along the user-to-satellite lines of sight, satellite elevations, and elevation rates. Now the user can identify the candidate population of satellites which are above a given elevation angle and remain above this criterion for some specified length of time. If the criterion is a minimum elevation angle of five degrees, and α represents satellite elevation and Δt represents the length of time over which the criterion must be satisfied, then the condition for

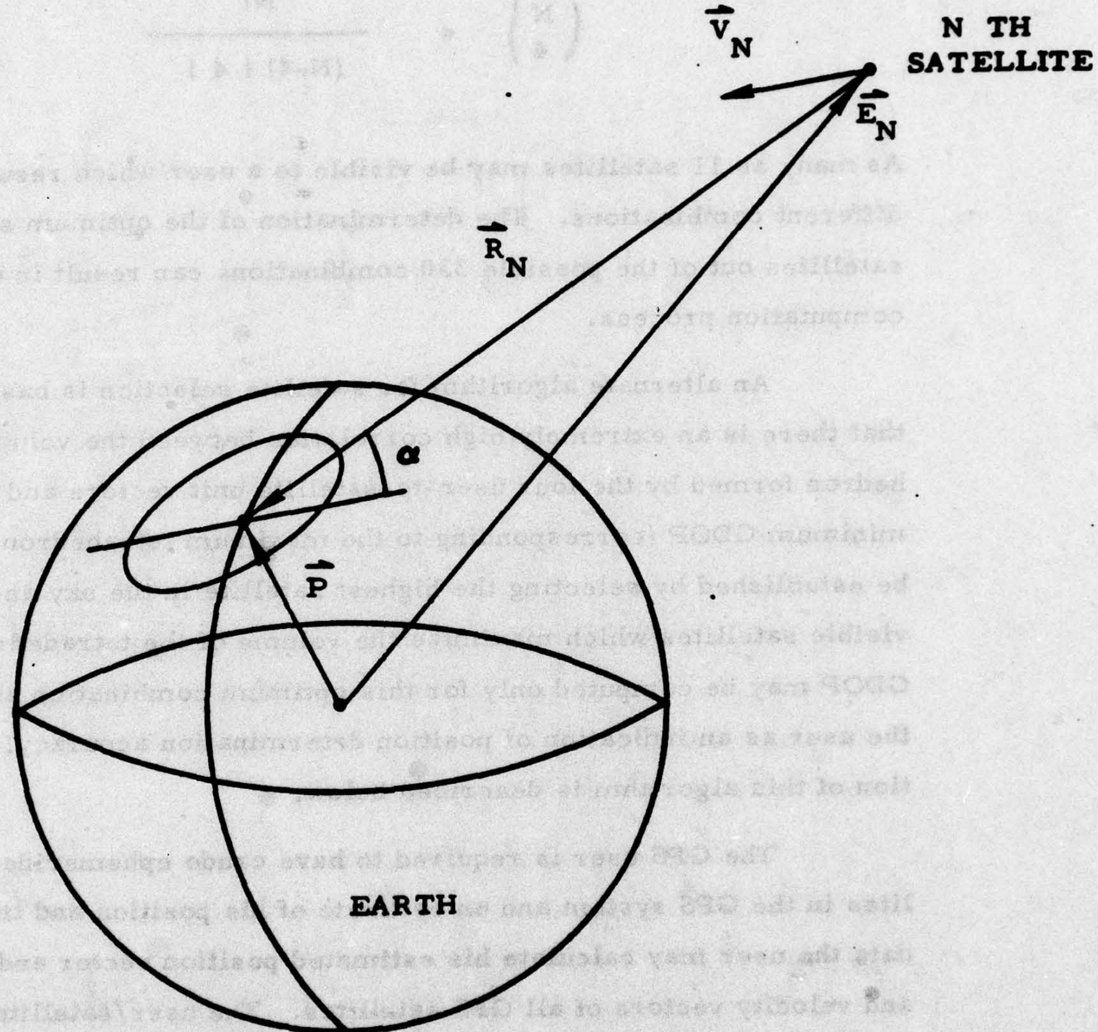


FIGURE 7. USER/SATELLITE GEOMETRY

a satellite to be a candidate may be stated as

$$\alpha + \dot{\alpha} \Delta t \geq 5 \text{ deg.}$$

The next step is to identify the highest satellite in the sky and all combinations of four satellites using the highest satellite and the remaining population taken three at a time. Then for each combination the volume and volume rate of change of the tetrahedron formed by the four unit vectors to each satellite may be determined. The mean geometric volume of all combination may be calculated based on the present time and some future time of interest. After checking all combinations to eliminate those combinations which have zero volume transitions during the time interval of interest, the combination which produce maximum mean volume may be selected. This comination will result in the best navigation performance over the time interval. After identifying the optimum set of four satellites the appropriate C/A signal codes may be selected to begin the signal acquisition process. This satellite selection process is summarized in Figure 8.

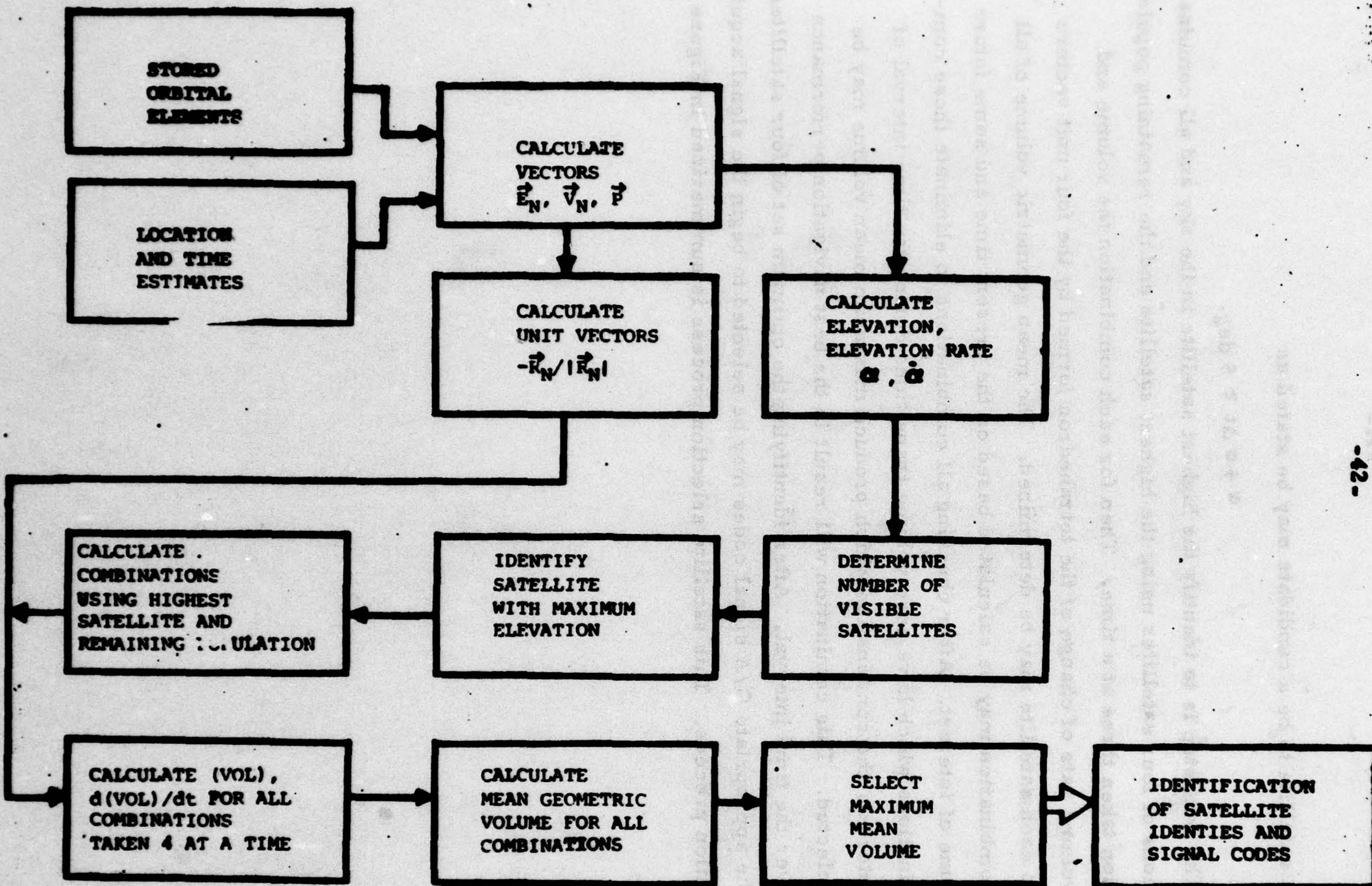


FIGURE 8. TYPICAL SATELLITE SELECTION METHOD

5.1.2 SIGNAL ACQUISITION

The general form of the signal received by a GPS receiver may be expressed as

$$S(t) = \sum_{i=o}^{N} S_i(t) = \sum_{i=o}^{N} \sqrt{2P_i}\; d_i(t)\, c_i(t) \cos(\omega_i t + \phi_i)$$

The composite signal consists of the signal to be acquired, denoted by the index "0", and a collection of N similarly constructed but undersired signals. In the above equation the variables are defined as follows:

P_i = average received power of $S_i(t)$

$d_i(t)$ = system data modulo 2 added to $c_i(t)$

$c_i(t)$ = PN code sequence

ω_i = carrier frequency

ϕ_i = Carrier phase

The discussion here will be limited to the normal acquisition mode where $c_i(t)$ is a Gold code sequence.

The signal detection process involves the correlation of a locally generated replica of the code to be acquired with the received signal. In general, the local code will not be in synchronism with the incoming code, so that the amplitude of the correlated signal depends on the properties of the quantity

$$\langle c_i(t)\, c_j(t+\tau) \rangle$$

The correlation properties of Gold codes are given in Section 3.3 of this report. For the GPS C/A code the normalized correlation properties are

$$R_i(\tau) = \begin{cases} 1 & \tau = 0 \\ <0.06 & \text{for } \tau \neq 0 \end{cases}$$

$$C_{ij}(\tau) < \sim 0.06$$

where τ is the code phase offset between local and incoming codes and the auto- and cross-correlation functions are defined as in Section 3.3. As a result, the first step in the signal acquisition process is to achieve code synchronization. This process must take place before loop tracking and data demodulation can be initiated.

Since the GPS receiver moves relative to the transmitter (satellite), the carrier frequency is subject to Doppler shifts, while both code epoch time and carrier phase depend on the distance between the receiver and the transmitter. In general, the receiver knows neither the exact velocity or distance relative to the transmitter. Hence, the receiver does not know carrier frequency, code epoch time, or carrier phase. However, the receiver can place some bounds on its position and velocity so that it knows that the carrier frequency is in some range Ω_f and the code epoch is in some range τ_c. Thus, the initial synchronism problem is one of searching for the signal in a rectangular (frequency vs. time) grid of total area $\Omega_f \tau_c$.

Because of the frequency uncertainty of the received carrier as well as the lack of knowledge of its phase, a non-coherent detection search throughout a bounded time uncertainty region is used. This detection scheme is based on the assumption that narrowly bounded frequency uncertainities allow a search in time only. Successive incremental step retardations of the locally generated reference PN code will ultimately result in a successful code correlation and therefore code synchronization. A block diagram of the synchronization search scheme is shown in Figure 9.

Two detection techniques may be used to determine signal presence. The first method is a fixed interval integration technique. This technique is based on specifying an interval, t_s, over which the waveform containing a possible signal is integrated and threshold sampled. The threshold value

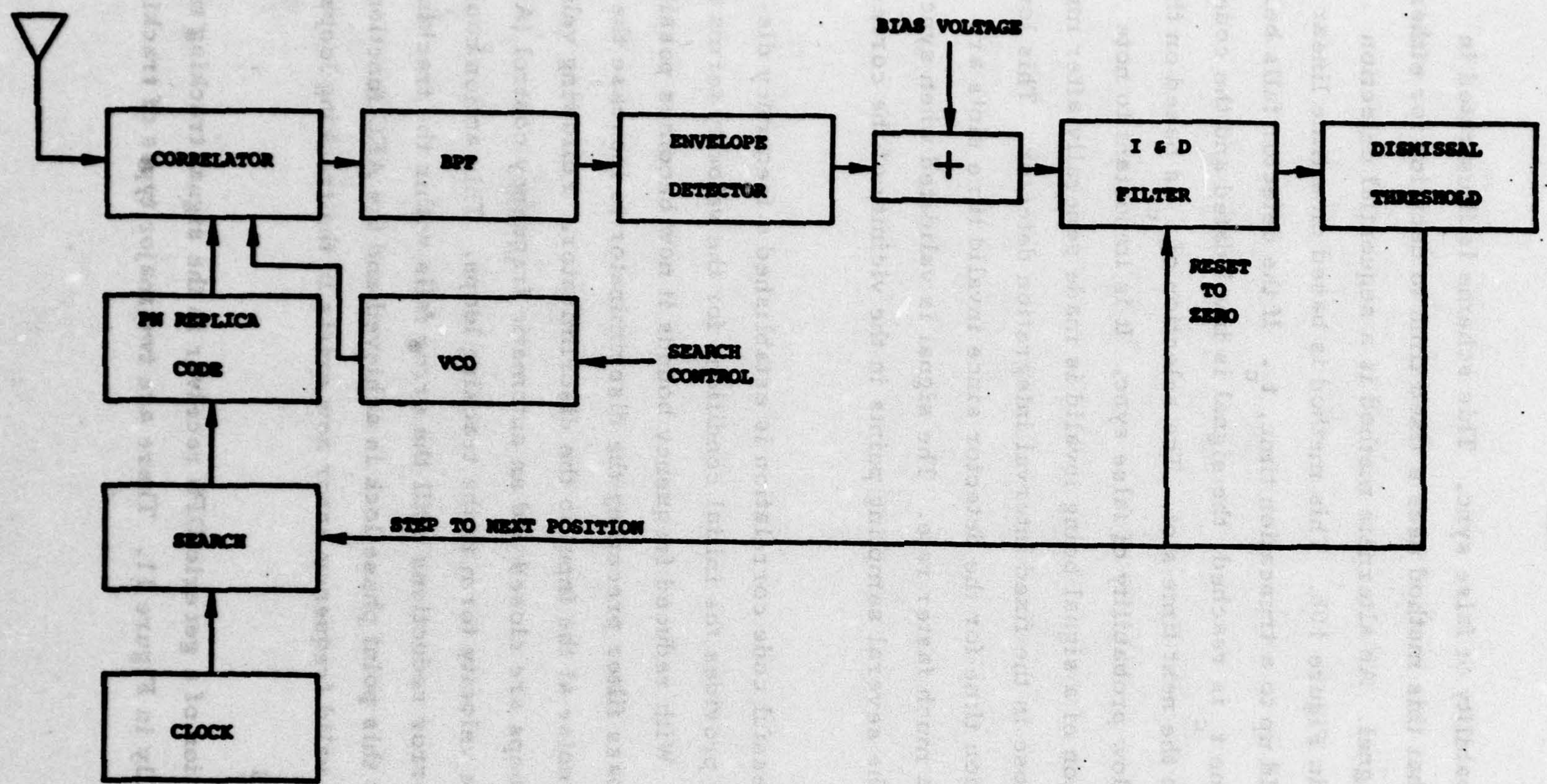


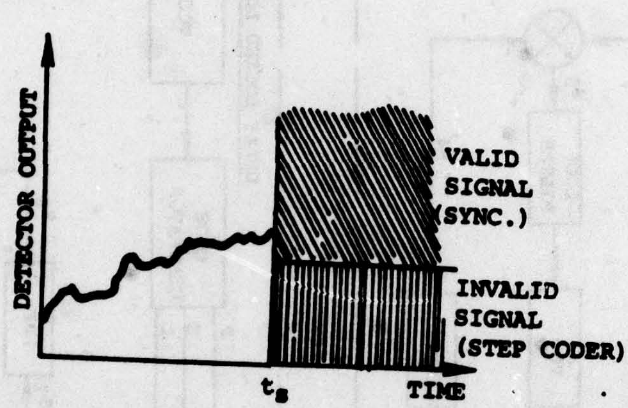
FIGURE 9. CODE SYNCHRONISM SEARCH SCHEME

is based on the probability of false sync. This scheme is illustrated in Figure 10a. Note that this method uses a fixed time to decision for either a valid or invalid signal. An alternate method is a sequential detection scheme illustrated in Figure 10b. This method is based on a time linear increase of threshold up to a truncation time, t_c. If the detector falls below threshold before time t_c is reached, the signal is invalidated and the coder is stepped to search the next time slot. The selection of t_c is based on the desired value for a low probability of false sync. It is important to note that the determination of a signal being invalid is made generally after much lower times than those in the fixed interval integration detector. This lowers the overall acquisition time for the detector since invalid time slots are stepped through at a much faster rate. The signal is validated when sync is achieved at one of the several sampling points in the vicinity of the correlation peak.

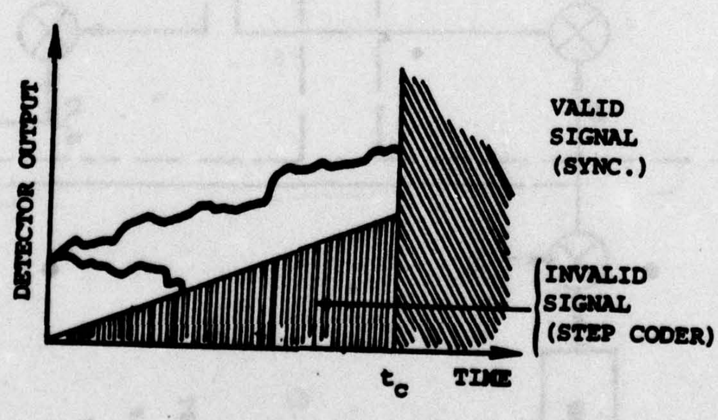
Once successful code correlation is established a frequency discriminator process provides the initial conditions for the velocity terms in the tracking loops. With reduced frequency bounds it now becomes possible to narrow the bandpass filter preceding the discriminator to increase the effective signal-to-noise at the input to the discriminator. Following velocity initialization, the loops are closed and an automatic frequency control (AFC) circuit advances the velocity term in the tracking loops. This action causes further frequency error reductions until the error falls within the tracking loop bandwidth. At this point phase lock is achieved and the AFC function is inhibited since a valid frequency error now exists in the tracking loops.

5.: <u>TRACKING</u>

The operation of a generic GPS receiver in the signal tracking mode is shown conceptually in Figure 11. There are two major types of tracking



a) FIXED INTERVAL INTEGRATION



b) SEQUENTIAL DETECTION

FIGURE 10. CODE SYNCHRONIZATION DETECTION TECHNIQUES

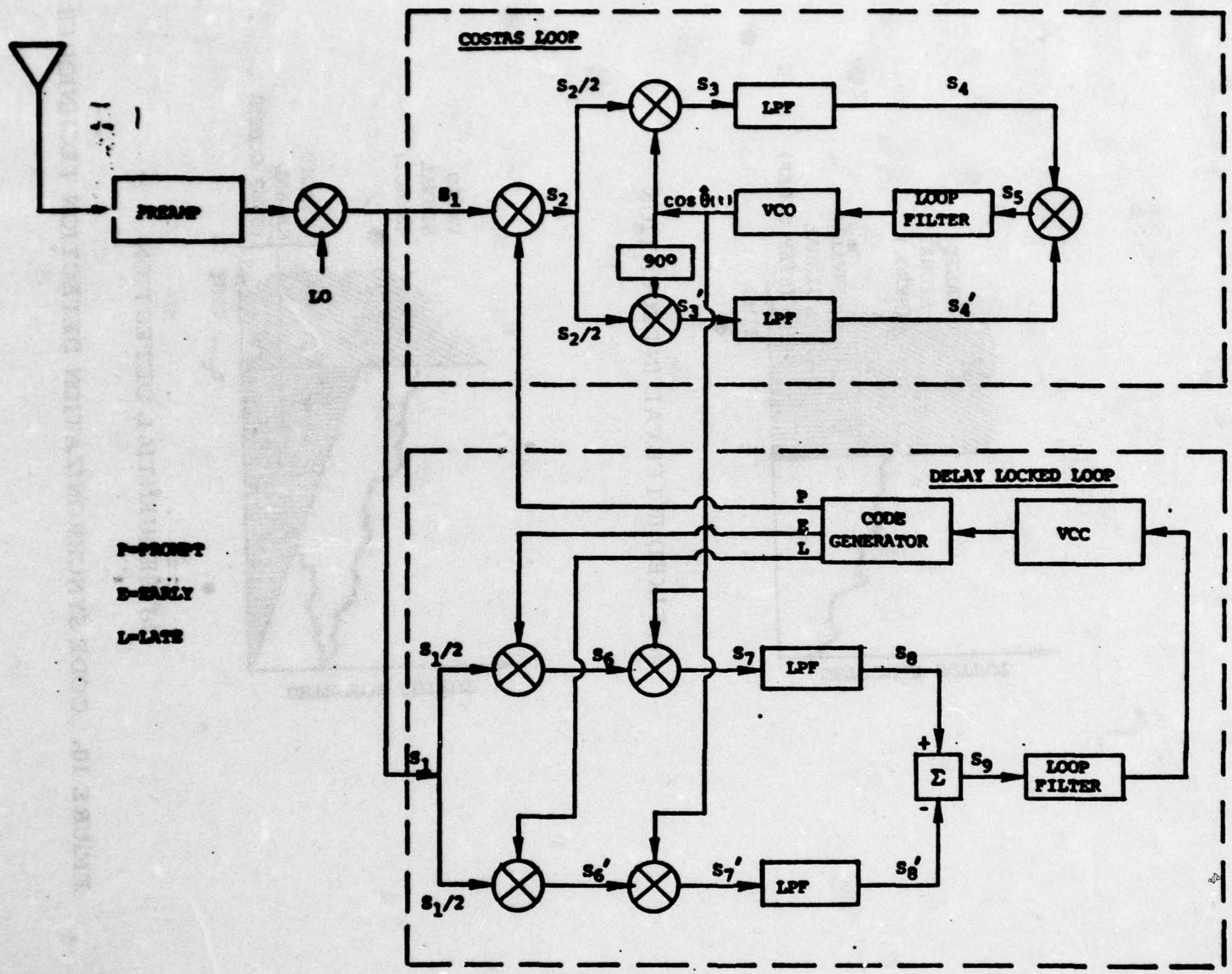


FIGURE 11. GENERIC GPS RECEIVER CONCEPT

loops employed. A Costas loop is employed to track the suppressed carrier signal to obtain satellite/user relative velocity information. In addition, the Costas loop provides a coherent frequency reference for the code tracking loop and data demodulation. The code tracking loop is implemented as a delay locked loop. The code tracking loop keeps the locally generated reference code in phase or bit synchronism with the received code. The basic operation of these two types of tracking loops will be briefly discussed to indicate the function and interdependence of the loops. The description of the loop will be based on an idealistic, simplified analysis of Costas and delay locked loop operation.

Consider a signal input to the Costas loop of the form (see Figure 11),

$$S_1(t) = Ad(t)\, c(t) \cos(\omega t + \phi)$$
$$= Ad(t)\, c(t) \cos \theta(t)$$

where

A = signal amplitude
d(t) = data sequence of (+1, -1)
c(t) = code sequence of (+1, -1)
ω = carrier frequency
ϕ = carrier phase

$\theta(t) = \omega t + \phi$

This signal is correlated with a locally generated replica of the incoming data code. For the purposes here, it is assumed that this "prompt" code is in sync with the incoming code so that

$$S_2(t) = S_1(t)\, c(t)$$
$$= Ad(t) \cos \theta(t)$$

Hence the code has been stripped off the signal. The signal is split and, in the upper arm of the loop, is multiplied by $\cos \hat{\theta}(t)$, where $\hat{\theta}(t)$ is the estimated signal phase.. Hence

$$S_3(t) = 1/2\ A\ d(t) \cos\theta(t) \cos\hat{\theta}(t)$$

$$= 1/4\ A\ d(t)\ [\cos(\theta(t) - \hat{\theta}(t)) + \cos(\theta(t) + \hat{\theta}(t))]$$

The frequency of the term $\theta(t) + \hat{\theta}(t)$ is of the order 2ω, and if it is assumed that this component is not passed by the low pass filter, the resulting filter output is

$$S_4(t) = 1/4\ A\ d(t) \cos\theta_e$$

where

$$\theta_e = \theta(t) - \hat{\theta}(t)$$

Similarly, the lower arm of the loop is multiplied by $\sin\hat{\theta}(t)$ so that

$$S_3'(t) = 1/2\ A\ d(t) \cos\theta(t) \sin\hat{\theta}(t)$$

$$= 1/4\ A\ d(t)\ [\sin(\theta(t) + \hat{\theta}(t)) - \sin(\theta(t) - \hat{\theta}(t))]$$

Again assuming that the double frequency term is not passed, the output of the low pass filter is

$$S_4'(t) = -1/4\ A\ d(t) \sin\theta_e$$

The resulting input to the loop filter is

$$S_5(t) = S_4(t)\ .\ S_4'(t)$$

$$= -1/16\ A^2 \cos\theta_e \sin\theta_e$$

$$= -1/32\ A^2 \sin 2\theta_e$$

for small errors

$$\sin 2\theta_e \cong 2\theta_e$$

so that

$$S_5(t) \cong (-1/16\ A^2)\ \theta_e$$

Hence, the input to the loop filter is a signal proportional to the VCO error. Controlling the VCO according to the error signal will cause the loop to track the frequency of the incoming signal. Doppler shifts, which are indicative of relative velocity between the satellite and user, may be measured by monitoring the VCO. It can also be noted that for small errors

$$S_4(t) \cong 1/4\ A\ d(t)$$

so that data demodulation has been performed in the tracking process. The detailed analysis of the performance of Costas loops in the presence of noise may be found in References 3 and 4.

The delay locked loop (DLL) tracks the code, c (t), to provide a synchronized reference code for correlation in the Costas loop. In addition, by monitoring the voltage controlled clock (VCC) which controls the code generator, the pseudorange between the user and satellite can be measured. The DLL achieves code tracking by correlating the input signal with early and late versions of the reference code. Referring to Figure 11, for the early channel

$$\begin{aligned} S_6(t) &= 1/2\ S_1\ .\ c\,(\hat{t} - \tfrac{\Delta}{2}) \\ &= 1/2\ A\ d(t)\ c(t)\ c(\hat{t} - \tfrac{\Delta}{2}) \cos\theta\,(t) \end{aligned}$$

where

$\hat{t}$ = estimated system time

Δ = time width of one code chip

This signal is then multiplied by $\cos\hat{\theta}(t)$ which is derived by the Costas loop. For the purposes here, it is assumed that $\cos\hat{\theta}(t) \cong \cos\theta\,(t)$ so that

$$\begin{aligned} S_7(t) &= 1/2\ A\ d(t)\ c(t)\ c(\hat{t} - \tfrac{\Delta}{2}) \cos^2\theta(t) \\ &= 1/4\ A\ d(t)\ c(t)\ c(\hat{t} - 2)\ [1 + \cos 2\,\theta\,(t)] \end{aligned}$$

If it is assumed that the double frequency term is not passed, the output of the low pass filter is

$$S_8(t) = 1/4\ A\ d(t)\ c(t)\ c(\hat{t} - \tfrac{\Delta}{2})$$

Since d(t) is just a (+1, -1) sequence, the magnitude of $S_8(t)$ depends on the properties of $c(t)\ c(\hat{t} - \frac{\Delta}{2})$. Representing $\hat{t}$ as

$$\hat{t} = t + \epsilon$$

where

$$\epsilon = \text{time estimate error}$$

the quantity

$$c(t)\ c(t + \epsilon - \tfrac{\Delta}{2})$$

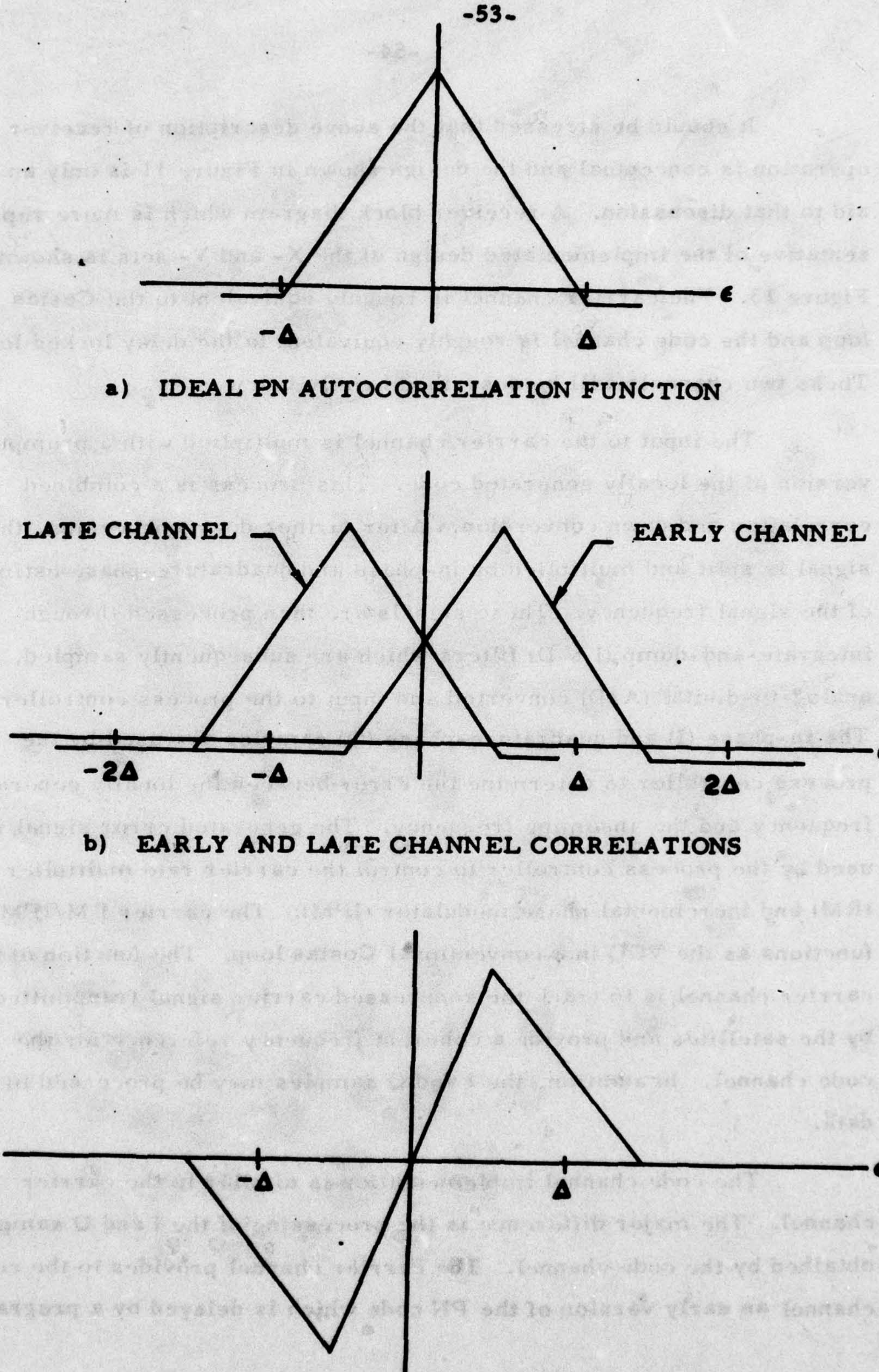
corresponds to the autocorrelation function

$$R\ (\epsilon - \tfrac{\Delta}{2})$$

The autocorrelation function of an ideal PN sequence is shown in Figure 12a. The autocorrelation function of the early channel, $R\ (\epsilon - \frac{\Delta}{2})$, shown in Figure 12b is a shifted version of the correlation function in Figure 12a. A similar development leads to

$$S'_8\ (t) = 1/4\ A\ d(t)\ c(t)\ c(\hat{t} + \tfrac{\Delta}{2})$$

where the correlation has been performed with a late version of the reference code. The corresponding autocorrelation function $R\ (\epsilon + \frac{\Delta}{2})$ is also shown in Figure 12b. The DLL discriminator characteristic is obtained by subtracting the early and late channels. The result is shown in Figure 12c. This DLL characteristic produces a linear tracking region $(-\frac{\Delta}{2}, \frac{\Delta}{2})$ which provides an error voltage proportional to the phase error between the local and incoming codes. This error signal is input to the loop filter which controls the VCC to provide code synchronization. The detailed analysis of the performance of delay locked loops in the presence of noise may be found in References 5, 6, and 7.



a) IDEAL PN AUTOCORRELATION FUNCTION

b) EARLY AND LATE CHANNEL CORRELATIONS

c) ERROR TRACKING CHARACTERISTICS

FIGURE 12. DLL DISCRIMINATOR CHARACTERISTIC

It should be stressed that the above description of receiver operation is conceptual and the design shown in Figure 11 is only an aid to that discussion. A receiver block diagram which is more representative of the implementated design of the X- and Y- sets is shown in Figure 13. The carrier channel is roughly equivalent to the Costas loop and the code channel is roughly equivalent to the delay locked loop. These two channels will be described briefly below.

The input to the carrier channel is multiplied with a prompt version of the locally generated code. This process is a combined correlation and down conversion. After further down conversion, the signal is split and multiplied by in-phase and quadrature-phase estimates of the signal frequency. These signals are then processed through integrate-and-dump (I & D) filters which are subsequently sampled, analog-to-digital (A/D) converted and input to the process controller (PC). The in-phase (I) and quadrature-phase (Q) samples are used by the process controller to determine the error between the locally generated frequency and the incoming frequency. The generated error signal is used by the process controller to control the carrier rate multiplier (RM) and incremental phase modulator (IPM). The carrier RM/IPM functions as the VCO in a conventional Costas loop. The function of the carrier channel is to track the suppressed carrier signal transmitted by the satellites and provide a coherent frequency reference for the code channel. In addition, the I and Q samples may be processed to obtain system data.

The code channel implementation is similar to the carrier channel. The major difference is the processing of the I and Q samples obtained by the code channel. The carrier channel provides to the code channel an early version of the PN code which is delayed by a programmable

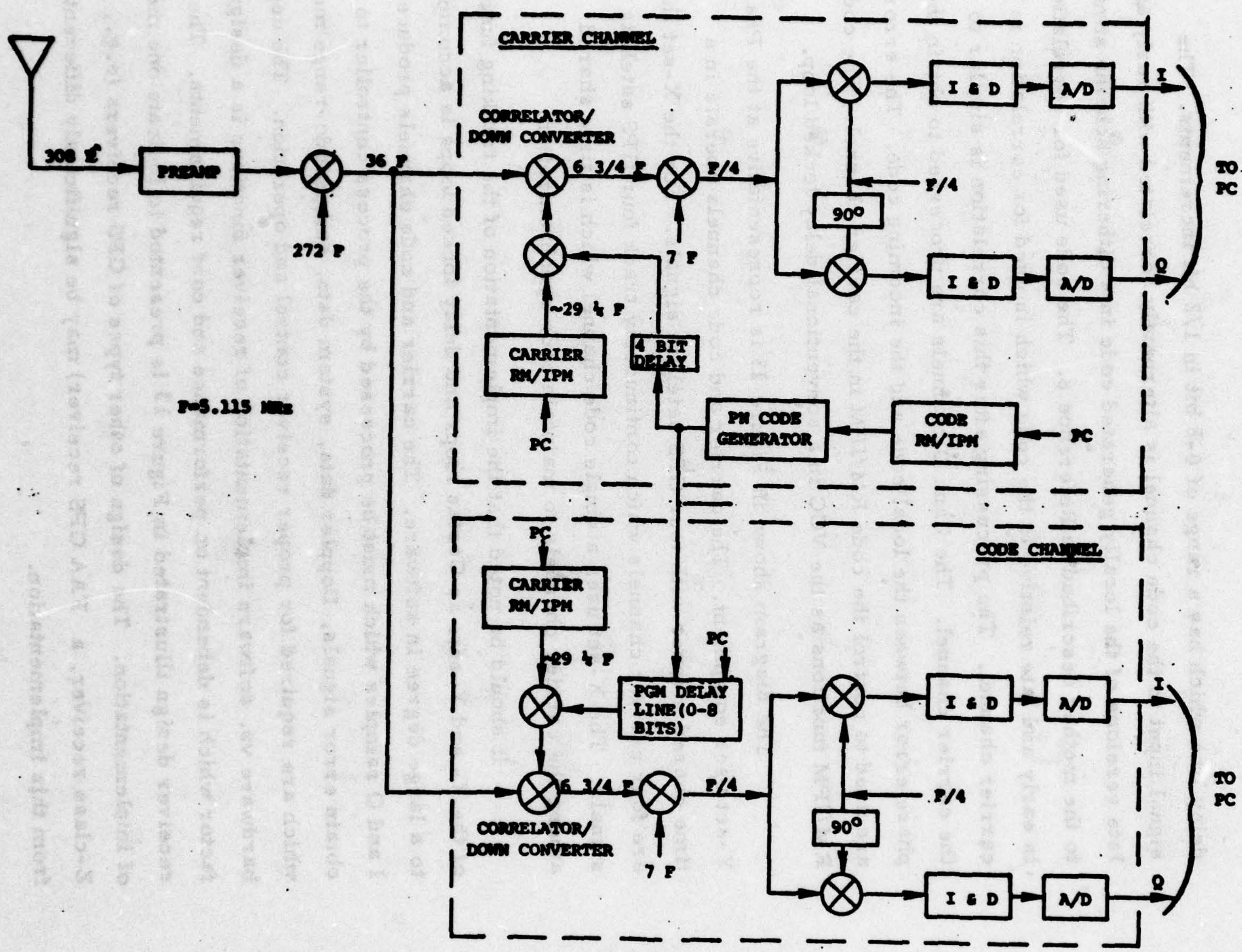


FIGURE 13. TYPICAL GPS RECEIVER IMPLEMENTATION

delay line which has a range of 0-8 bit in 1/2 bit increments. The signal input to the code channel is alternately correlated with early and late versions of the locally generated code in a dithering scheme similar to the method described in Reference 8. The code used for correlation is early and late relative to the code which is used for correlation in the carrier channel. The processing after this correlation is similar to the carrier channel. The I and Q channels are processed to obtain the phase error between the local code and the incoming code. The error signals are used to control the code RM/IPM in the carrier channel. The code RM/IPM functions as the VCC in a conventional delay locked loop.

The diagram shown in Figure 13 is representative at the Phase I Y-set user equipment. The carrier and code channels operate in a time shared manner with four GPS satellite signals. For the X-set there are four carrier channels which continuously track four GPS satellite signals. The X-set uses a single code channel which is time shared among the carrier channels to maintain code synchronization.

It should be noted that the implementation of the tracking functions of the X- and Y-sets as Costas loops and delay locked loops is accomplished to a large degree in software. The carrier and code channels produce I and Q samples which must be processed by the process controller to obtain error signals, Doppler data, system data, and pseudo-range measurements which are required for proper receiver control and operation. The degree of hardware vs. software implementation of receiver functions is a design factor which is dependent on performance and cost requirements. The receiver design illustrated in Figure 13 is presented to indicate one method of implementation. The design of other types of GPS receivers (e.g., the Z-class receiver, a FAA GPS receiver) may be significantly different from this implementation.

5.3 X-SET AND Y-SET MAJOR COMPONENT CHARACTERISTICS

A function block diagram of the X-receiver major components is shown in Figure 14. The Y-receiver is similar but will have only one

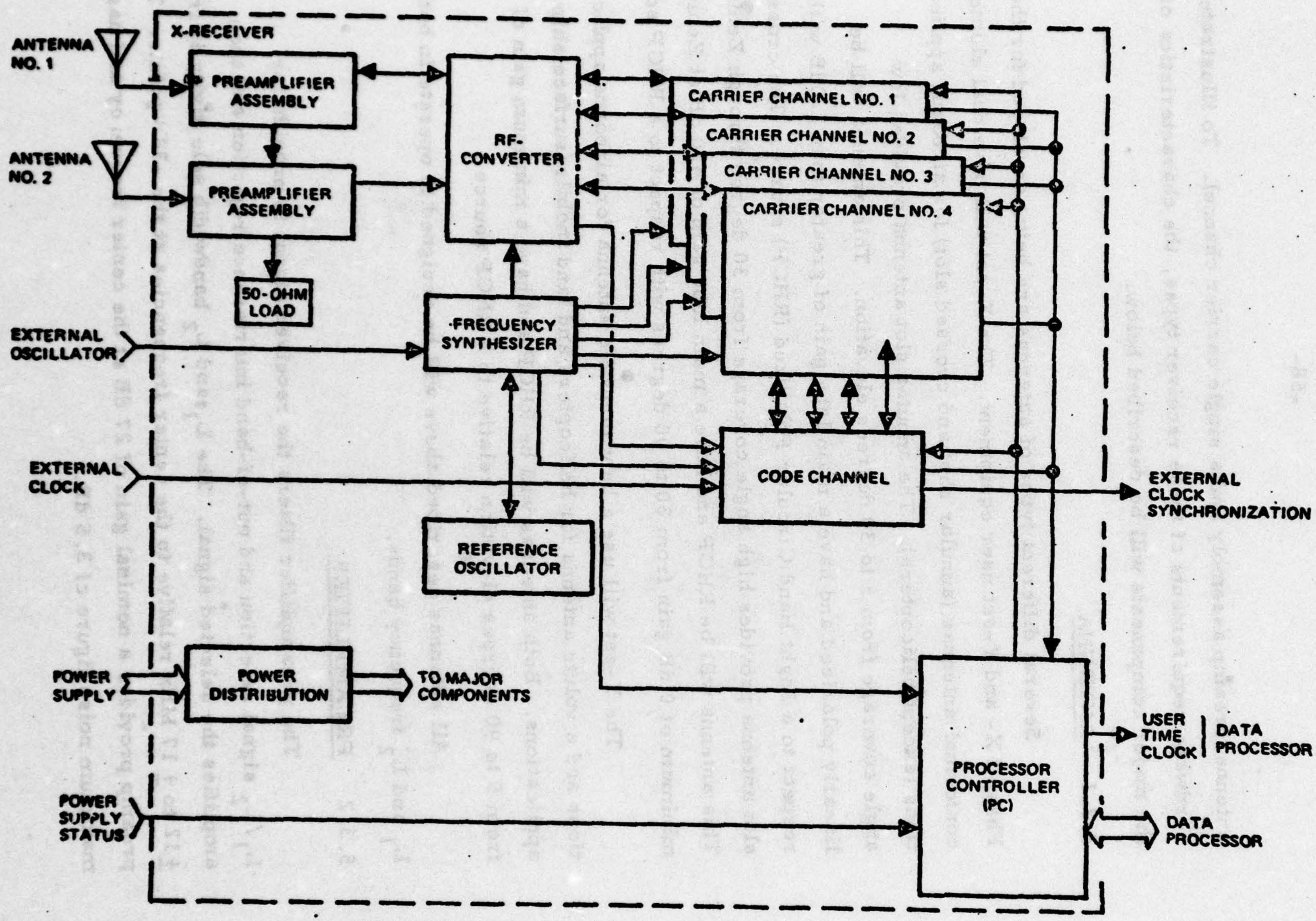


FIGURE 14. X-RECEIVER MAJOR COMPONENTS FUNCTIONAL BLOCK DIAGRAM

antenna/preamp assembly and a single carrier channel. To illustrate the hardware requirements of these receiver types, the characteristics of the major components will be described below.

5.3.1 ANTENNA

Several different types of antennas are being developed for the Phase I X- and Y-set user equipment. The X-set will have dual element conformal antennas (annular shot and crossed slot) for airborne applications (except helicopters). The annular slot antenna provides low angle coverage from 5 to 30 degrees elevation. This antenna will be linearly polarized and have a main lobe gain of greater than 1.0dB with respect to a Right Hand Circular Polarized (RHCP) source. The crossed slot antenna provides high angle coverage from 30 degree through Zenith. This antenna will be RHCP and have a main lobe gain of 4.0 dB at Zenith and a minimum of 0 dB gain from 30 to 90 degrees with respect to a RHCP source.

The Y-set will use a bent turnstile antenna for airborne applications and a volute antenna for helicopters and land mobile/surface ship applications. Both antennas will be RHCP and have a minimum gain of 0 dB from 5 to 90 degrees elevation relative to a RHCP source.

All antennas described above will be designed to operate in both L_1 and L_2 frequency bands.

5.3.2 PREAMPLIFIER

The preamplifier filters the received signal to provide for L_1/L_2 signal selection and out-of-band interference rejection and then amplifies the selected signal. The L_1 and L_2 bandwidth sele:tivity is from ± 12 to ± 17 MHz relative to the center frequencies at the -3d:: points. The preamp provides a nominal gain of 27 dB at the center freque: cy and has a maximum noise figure of 3.5 dB.

5.3.3 RF CONVERTER

The RF converter accepts the RF input(s) from the preamplifier(s), bandpass filters the signal(s), and downconverts the signals (both L_1 and L_2 to a frequency of 184.14 MHz.

5.3.4 FREQUENCY SYNTHESIZER

The frequency synthesizer generates the required frequencies for all receiver local oscillators and user timing. All frequencies are derived from the reference oscillator input at 5.115 MHz(F). The synthesized frequencies are 2F, 4F, 7F, 17F, 21F, 34F, 204F, 272F, and 274F. In addition, the frequency synthesizer can phase-lock the receiver oscillator to an external oscillator source.

5.3.5 REFERENCE OSCILLATOR

The reference oscillator is the frequency source from which all receiver LO frequencies and timing are synthesized. The nominal output frequency is 5.115 MHz. The following are the fractional stability ($\frac{\Delta F}{F}$) requirements of the reference oscillator.

Total deviation over temperature range (-20 to +60 °C)	$< 1 \times 10^{-9}$
Short term	$< 1 \times 10^{-10}$ / sec.
Aging rate	$< 1 \times 10^{-9}$ / 24 hr.

5.3.6 CARRIER CHANNEL

The carrier channel generates any one of the unique PN code sequences for the P and C/A signals. The locally generated code replica is cross-correlated with the input signal. The results of this correlation process are supplied to the process controller.

5.3.7 CODE CHANNEL

The code channel accepts early phase versions of the locally generated code replica and cross-correlates early and late versions of this code with the input signal. The results of this correlation process are supplied to the process controller.

5.3.8 PROCESS CONTROLLER

The process controller performs the following receiver control and signal processing functions:

a) Initialization & Calibration

b) Sequential Search

c) Costas Loop Tracking

d) Code Tracking

e) RM, IPM & PN Coder Management

f) Data Demodulation and Error Detection

g) Selection of Discrete Loop Bandwidths (Code and Carrier)

h) UT Clock Management

i) Automatic Gain Control

j) Measurements (Pseudorange/Delta Range/L_1-L_2)

h) Monitor Functions (Signal Quality/AFI)

The process controller is a microprocessor that is being developed by Magnavox for the X- and Y-sets to interface with the receiver channels and the data processor. The process controller obtains I and Q samples from the receiver channels and processes these samples to control the operation of the receiver and measure pseudorange. The pseudorange measurements are sent to the data processor which performs the navigational computations. The data processor provides estimates of pseudorange and pseudorange rate to the process controller for loop aiding. A more complete description of the information flow between the receive channels, process controller, and data processor is shown in Figure 15.

5.3.9 DATA PROCESSOR

The data processor is a commercial unit manufactured by Hewlett Packard (HP 21MX). As shown in Figure 15, the data processor receives

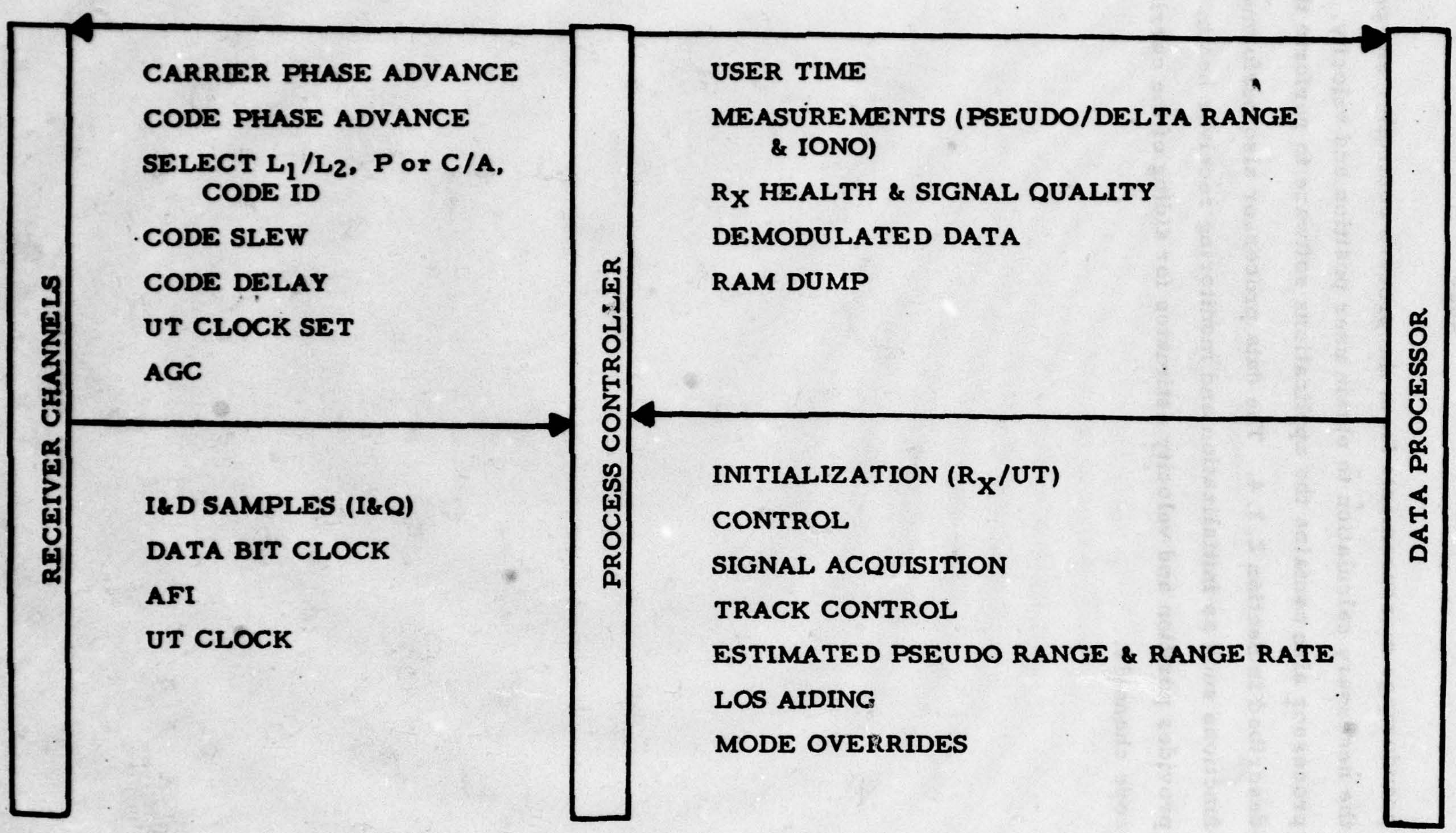


FIGURE 15. PROCESS CONTROLLER INFORMATION FLOW

pseudorange measurements from the process controller and performs the necessary calculation to obtain user position and velocity. The data processor also contains the applications software to perform the functions described in Section 2.3.4. The data processor also performs executive functions such as initialization and monitoring receiver heath, and provides position and velocity estimates for aiding of the carrier and code channels.

6. USE OF GPS IN THE AEROSAT PROGRAM

This section will discuss the operational concepts which may be employed in the use of GPS in the AEROSAT Test and Evaluation Program. Three options will be presented which embody these operational concepts and represent varying degrees of integration of GPS user equipment and the AEROSAT avionics. These options are not exhaustive but represent a range of approaches which may be taken to utilize the GPS "resource" as part of the AEROSAT Program. Experiments with GPS will allow the FAA to obtain operational experience with GPS, and allow the collection of data which may be used to assess the impact of GPS on an operational AEROSAT system. This section will discuss some of the technical considerations including performance requirements and the impact on the AEROSAT avionics design.

6.1 OPERATIONAL CONCEPTS

Two operational concepts may be employed in the use of GPS in the AEROSAT Program. The primary difference between these concepts is where the signal processing is performed.

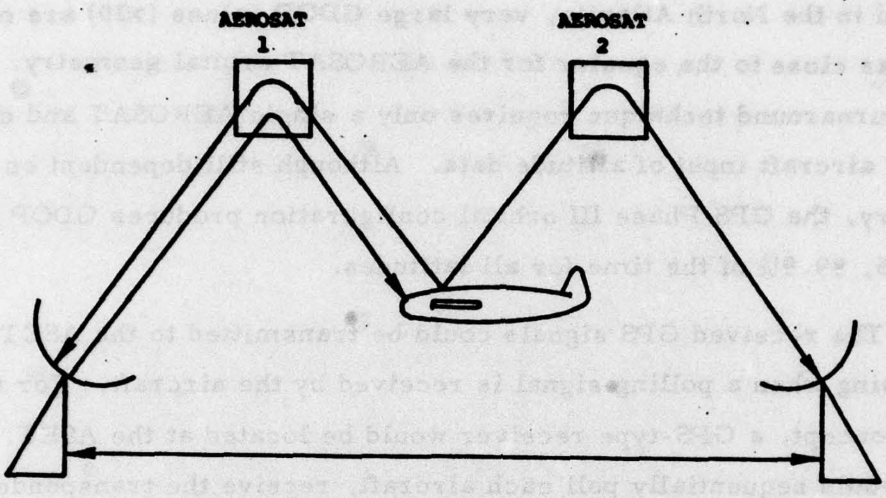
In the first operational concept, the GPS signals are received and processed by equipment located in the aircraft. To provide surveillance, the pilot could periodically report his position to air traffic control in a manner similar to current oceanic operation. An AEROSAT return voice or data channel could be used for this position reporting. Alternately, the reporting of navigation data could be automated using one of two methods. The navigation data could be requested by polling each aircraft using a forward AEROSAT channel with the navigation data necessary for surveillance automatically transmitted to air traffic control via an AEROSAT return channel. For this method, the timing of surveillance reporting is controlled by the ground. The alternate automatic reporting method is to utilize the system time which is obtained in the solution of the navigational equations.

Since all aircraft in the system are synchronized with system time (within a certain accuracy), each aircraft could be assigned an unique time slot in which to transmit the surveillance data. The advantage of this method is that it may eliminate the need for one forward channel which is dedicated to aircraft polling.

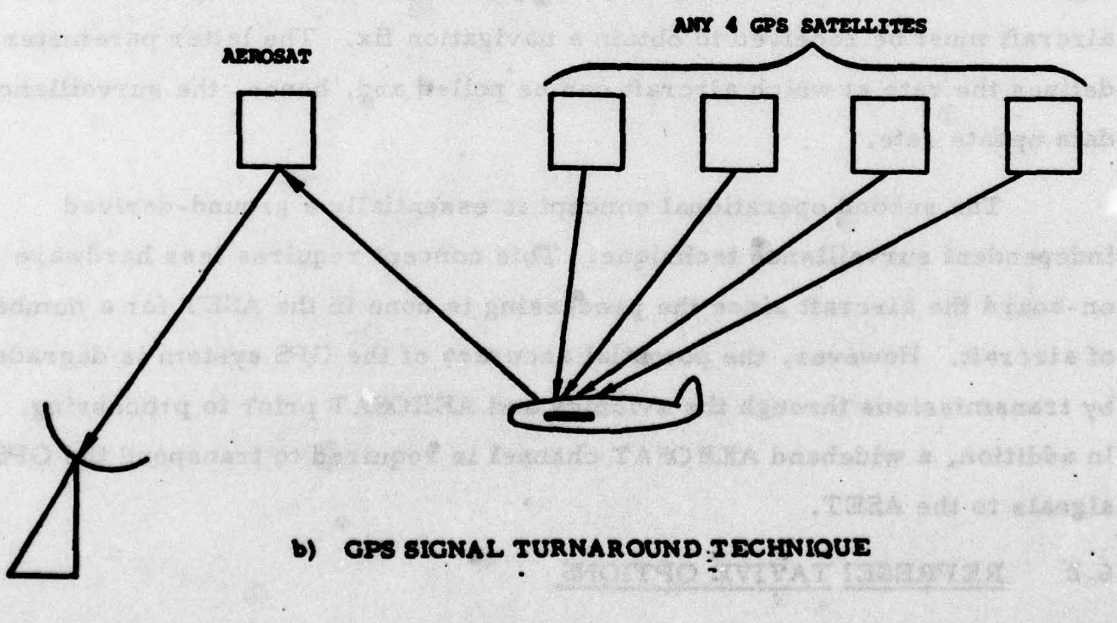
This operational concept is essentially an air-derived dependent surveillance technique. This requires the aircraft to have the receiver hardware and computer resources necessary to perform signal processing and navigational computations. Depending on the implementation, it may be possible to use a common RF front end and computer for both AEROSAT and GPS operation. This would eliminate equipment duplication. An advantage of this operational concept is that it also provides navigation data to the pilot. The navigation data could be used to drive a cockpit display or be used in conjunction with other navigation equipment. For example, inertial navigation systems (INS) drift and, as a result, have an accuracy on the order of one nautical mile per hour. The GPS navigation data could be used to provide periodic updates to the INS for drift correction. The INS could provide position and velocity estimates to the GPS equipment to aid GPS signal acquisition/re-acquisition operations.

In the second operational concept, the GPS signals are received by the aircraft and transponded unprocessed via AEROSAT to the ASET and ASCC for processing. This concept is similar to the AEROSAT independent surveillance technique where the received ranging signals are transponded by the avionics via AEROSAT to the ground for processing. The differences between the normal AEROSAT ranging and GPS signal turnaround schemes are illustrated in Figure 16.

The AEROSAT ranging technique requires two AEROSATS, two ASETS, a minimum of three ETS, and communications between the various ground stations. In addition, the aircraft is required to supply altitude data to the



a) AEROSAT RANGING TECHNIQUE



b) GPS SIGNAL TURNAROUND TECHNIQUE

FIGURE 16. AEROSAT AND GPS SURVEILLANCE TECHNIQUES

ASET to obtain a positional fix. Although good GDOP values (3-4) are obtained in the North Atlantic, very large GDOP values (>30) are obtained for areas close to the equator for the AEROSAT orbital geometry. The GPS signal turnaround technique requires only a single AEROSAT and does not require aircraft input of altitude data. Although still dependent on orbital geometry, the GPS Phase III orbital configuration produces GDOP less than 4.5, 99.9% of the time for all latitudes.

The received GPS signals could be transmitted to the ASET for processing when a polling signal is received by the aircraft. For this operational concept, a GPS-type receiver would be located at the ASET. The ASET would sequentially poll each aircraft, receive the transponded signals for some length of time, and perform the necessary processing and computation. The two critical parameters for this technique are the quality of the signal received at the ASET and the length of time which a signal from an aircraft must be received to obtain a navigation fix. The latter parameter defines the rate at which aircraft can be polled and, hence, the surveillance data update rate.

The second operational concept is essentially a ground-derived independent surveillance technique. This concept requires less hardware on-board the aircraft since the processing is done in the ASET for a number of aircraft. However, the potential accuracy of the GPS system is degraded by transmissions through the avionics and AEROSAT prior to processing. In addition, a wideband AEROSAT channel is required to transpond the GPS signals to the ASET.

6.2 REPRESENTATIVE OPTIONS

This section presents three options which characterize the two operational concepts previously described and illustrate degrees of GPS and AEROSAT avionics implementation commonality. The three options are depicted in Figure 17 and are described below.

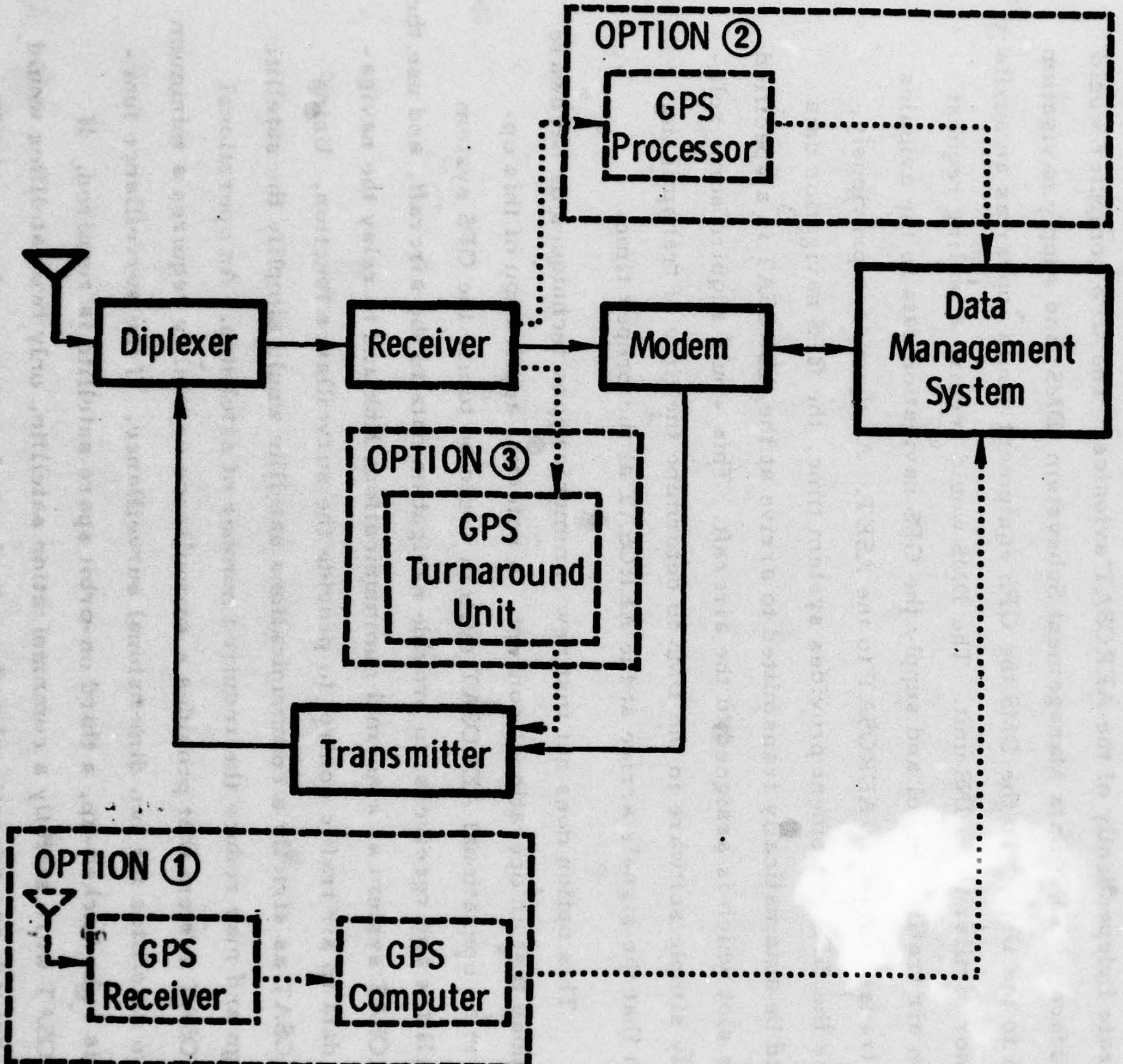


FIGURE 17. AEROSAT AVIONICS WITH OPTIONS FOR GPS USAGE

6.2.1 USE OF "AS-DESIGNED" GPS USER EQUIPMENT

An obvious way to use GPS in the AEROSAT program is to simply install an "as-designed" GPS user set in a test aircraft. This system would operate independently of the AEROSAT avionics. The GPS computer would interface with the Data Management Subsystem (DMS) and supply navigation data to the DMS. To the DMS the GPS equipment would appear as an auxilary sensor similar to an INS unit. The DMS would receive a polling request from air traffic control and supply the GPS navigation data to the avionics for transmission via AEROSAT to the ASET. As discussed previously, since the GPS equipment provides system time, the GPS navigation data could be automatically transmitted to arrive at the AEROSAT in a specified time slot which is assigned to the aircraft. This would require some relatively simple software in the DMS to determine the time of transmission such that the signals arrive at the AEROSAT at the proper time.

This option does not test new communications techniques or hardware but does test an operational concept. A potential application of this option in an operational AEROSAT system would be to use the GPS system (satellites and receivers) to provide navigation data to the aircraft, and use the AEROSAT system as a normal communications link and to relay the navigation data to air traffic control to provide the surveillance function. Using AEROSAT as strictly a communications satellite would simplify the satellite design and may reduce the required number of satellites. An operational AEROSAT system that provides a surveillance capability requires a minimum of two satellites for two dimensional surveillance. If the surveillance function is t› be backed-up, a third on-orbit spare satellite is required. If AEROSAT were strictly a communi-ation satellite, only two satellites would be requi ed; one operational and one backup. In addition, the use of GPS for surveillance reduces the number of ground stations (ETS) required for system operation.

This option has the least impact on the AEROSAT test avionics design since only a computer to computer interface is required. This option would represent the most expedient way to obtain operational experience and test data with GPS. However, it probably represents the costliest approach of the three options for an operational system. Since the AEROSAT and GPS avionics operate in parallel, duplication of equipment (RF front ends and computers) occurs. The second option discussed below addresses the development of a GPS signal processor which uses a RF front end and computer which is common with the AEROSAT equipment.

This option for use of GPS in the AEROSAT program is similar to the way in which GPS will be used in the MARISAT program. RCA Globecom will be procuring GPS terminals for the MARAD. These terminals will be placed on ships to provide a navigation capability. This data will then be relayed via MARISAT for surveillance.

6.2.2 DEVELOPMENT OF GPS SIGNAL PROCESSOR

The second option for use of GPS in the AEROSAT program is to develop a GPS signal processor. The GPS user equipment consists of a RF front end (antennas, preamps, and downconverters), a signal processing section (carrier and code tracking loops, process controller) and a data processor. Conceptually, it is feasible to use the RF front end of the AEROSAT avionics to receive and downconvert the GPS signal and to use a portion of the avionics data management subsystem (DMS) as the data processor. This configuration would be functionally similar to the first option but would eliminate the need for two RF front ends and data processors.

A block diagram of a typical configuration is shown in Figure 18. For the moment it is assumed that the antennas and other AEROSAT avionics equipment are compatible with the GPS signals. The GPS signal processor interfaces with the AEROSAT wideband channel second IF (70 MHz). It is assumed that the second IF local oscillator is tuned such that the GPS carrier

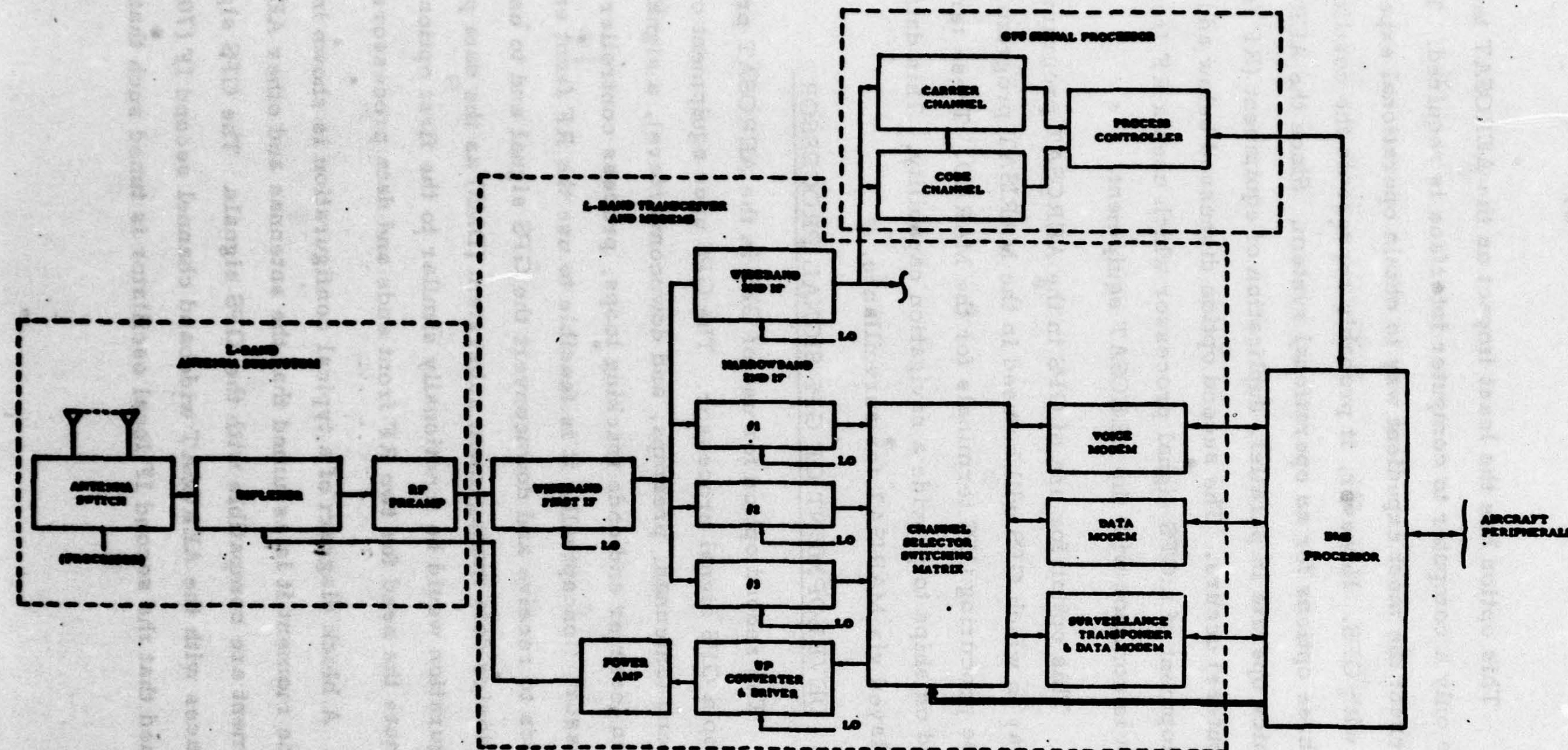


FIGURE 18. AEROSAT AVIONICS AND GPS SIGNAL PROCESSOR

frequency is translated to 70 MHz. The GPS signal processor performs the functions of carrier and code tracking, data demodulation, and pseudo range measurement. The processed GPS signals would be input to the DMS for navigation computations. When an aircraft is polled using an AEROSAT forward channel, the DMS could provide the GPS navigation data to the avionics data modem for transmission to the ASET via an AEROSAT return channel to provide the surveillance function. As with Option 1, the surveillance data could be transmitted automatically if the timing information provided by GPS is utilized.

The GPS signal processor shown in Figure 18 has a carrier channel, a code channel, and a process controller similar to the design of the X- and Y-sets described previously. However, the implementation and method of signal processing may differ for the AEROSAT application depending on the requirements for acquisition time, accuracy, etc. The input IF frequency to the carrier and code channels for the X- and Y-receivers is 184.14 MHz so that it may not be possible to use the processing sections of the GPS receivers directly. The Z-class receiver is just in the initial design stages and the IF and processing design for this class of receiver is unknown. Once the performance requirements of the GPS processor are defined and the designs of the AEROSAT avionics and the GPS sets that are under development are analyzed, the optimum processing method and implementation technique may be determined for the AEROSAT application.

Compared with Option 1, this option represents a more cost effective approach to a combined AEROSAT/GPS avionics package. This is due to the elimination of functionally similar pieces of equipment (RF front ends and general purpose computers). However, this does place certain restrictions of the design of the avionics to ensure compatibility between GPS and the AEROSAT system. Section 6.3 will discuss some of the design implications of a combined GPS/AEROSAT avionics set.

6.2.3 GPS SIGNAL TURNAROUND

The third option for use of GPS in the AEROSAT program is to transpond the GPS signal through the AEROSAT avionics and transmit the unprocessed signal via the AEROSAT wideband channel to the ASET for processing. This technique was illustrated in Figure 16b. This configuration would be similar to the Trident tracking tests which will be conducted by the Navy. For these tests, the GPS signal are received by a Trident and transponded to a tracking ship for processing.

To determine the feasibility of this option, link calculations were made to determine the received C/N_o at the ASET. The results are shown in Table X for the AEROSAT reference avionics, the satellite characteristics given in Reference 9, and the propagation margins specified in the Memorandum of Understanding. The resulting C/N_o of 16.8 dB-Hz is not sufficient for GPS receiver operation. The approximate threshold for carrier tracking from the GPS receiver Costas Loop is 25 dB-Hz. The link quality is dominated by the aircraft to AEROSAT return link. Most of the aircraft total EIRP is noise with only 7.6 dBW signal power.

Table XI gives the link calculations for a 6 dB increase in the aircraft avionics G/T and EIRP. The resulting C/N_o of 28.8 dB-Hz is marginal but should provide adequate quality for system operation. For example, Reference 7 gives the normalized delay locked loop tracking error for phase coherent correlation as

$$\sigma/\Delta = \sqrt{\frac{B_n}{2(C/N_o)}}$$

where

σ = standard deviation of tracking error

Δ = range equivalent of one chip

= 300 meters for the C/A code

B_n loop noise bandwidth

TABLE X

GPS TURNAROUND LINK BUDGET

REFERENCE AVIONICS AND MARGINS

GPS TO AIRCRAFT

GPS Power at Earth Surface	- 160 dBW (0dB antenna)
Aircraft G/T	- 26 dB/^{o}K
Received C/N_o	42.6 dB-Hz
Received C/N	- 27.4 dB

AIRCRAFT TO AEROSAT

Signal EIRP (Total EIRP = 23 dBW) (C/N = - 27.4 dB)	- 4.4 dBW
Path Loss	- 189 dB
Propagation Margin	- 5 dB
Polarization Loss	- 0.6 dB
Satellite G/T	- 11.3 dB/^{o}K
Received C/N_o	18.3 dB-Hz
Received C/N	- 51.7 dB

AEROSAT TO ASET

Signal EIRP (Total EIRP = 16.7 dBW) (C/N = - 51.7 dB) (C/I = 14 dB)	- 35 dBW
Path Loss	- 199 dB
Propagation Margin	- 2 dB
Polarization Loss	- 0.3 dB
ASET G/T	30 dB/^{o}K
Received C/N_o	22.3 dB-Hz

TOTAL

C/N_o	16.8 dB-Hz

TABLE XI

GPS TURNAROUND LINK BUDGET

6 DB INCREASE IN AIRCRAFT G/T AND EIRP

GPS TO AIRCRAFT

GPS Power at Earth Surface	- 160 dBW (0dB antenna)
Aircraft G/T	- 20 dB/°K
Received C/N_o	48.6 dB-Hz
Received C/N	- 21.4 dB

AIRCRAFT TO AEROSAT

Signal EIRP (Total EIRP = 29 dBW) (C/N = - 21.4 dB)	7.6 dBW
Path Loss	- 189 dB
Propagation Margin	- 5 dB
Polarization Loss	- 0.6 dB
Satellite G/T	- 11.3 dB/°K
Received C/N_o	30.3 dB-Hz
Received C/N	- 39.7 dB

AEROSAT TO ASET

Signal EIRP (Total EIRP = 16.7 dBW) (C/N = -39.7 dB) (C/I = 14 dB)	- 23 dBW
Path Loss	- 199 dB
Propagation Margin	- 2 dB
Polarization Loss	- 0.3 dB
ASET G/T	30 dB/°K
Received C/N_o	34.3 dB-Hz

TOTAL

C/N_o	28.8 dB-Hz

For a typical loop noise bandwidth of 1 Hz, the resulting tracking error is

$$\sigma = 7.7 \text{ meters}$$

for $C/N_o = 28.8$ dB-Hz. This tracking error should be viewed as only an order of magnitude estimate of receiver tracking error for an ideal case. The actual error depends on a detailed analysis to determine the effect of signal distortion caused by the transponding of the received GPS signals through the avionics and AEROSAT.

A total link quality in the range of 25-30 dB-Hz is marginal for receiver acquisition and tracking. Once AEROSAT avionics and satellite designs are known in greater detail and surveillance accuracy requirements are known, a more quantitative analysis of system feasibility and performance can be made. If system performance is such that data demodulation and decoding cannot reliably be performed from the signal received at the ASET, a possible alternative is to obtain the satellite data directly from the master control station via a land line. The system data contained in the navigation signals consists of satellite ephemeris, clock errors, and ionospheric data which is uploaded to the satellite. Since the ASCC would perform the navigation processing for all aircraft, the system data could be obtained directly from the GPS master control station to avoid the necessity of demodulating this data from transponded signals.

A critical system parameter for this option is the time-to-first-fix (TTFF). The time-to-first-fix is defined as the amount of time required to produce a single-point navigation solution from start of the navigation signal acquisition mode. In the normal operation of a GPS receiver, the receiver acquires the signals in the TTFF time and then tracks the signals making the navigation information available essentially continuously (a function of update rate). For the GPS signal turnaround option, the ASET would poll an aircraft and process the received GPS signal which has been transponded through AEROSAT. If no a priori information on aircraft

position is available, the problem presented to the GPS receiver located in the ASET is a time-to-first-fix problem. As shown in Table IV, the TTFF is a function of receiver implementation, interference levels, and vehicle state uncertainties. The TTFF times range from approximately 100 to 300 seconds. A large portion of this time is due to the demodulation of the system data which is transmitted at 50 bps. For the current data frame length of 1500 bits, this results in 30 seconds per channel. Receivers which process signals simultaneously require 30 seconds to obtain a full data frame, whereas receivers which process signals sequentially require 120 seconds (4 x 30) to obtain complete data frames. As previously stated, system data could be obtained directly from the GPS master control station and the requirement and time for data demodulation could be eliminated.

Most of the rest of the TTFF time is associated with signal acquisition requirements due to satellite and aircraft dynamics. A priori information of aircraft and satellite positions and velocities may be used to speed up the signal acquisition process and, hence, reduce the time to obtain an aircraft position fix. For example, based on the last aircraft position and velocity fix, the state vector of the aircraft may be estimated at the next surveillance interval and used as the initial conditions for the acquisition process. The resulting time to signal acquisition is a function of previous state vector determination errors, aircraft dynamics between updates, and the sophistication of the software employed to provide aircraft state vector predictions.

If the time to obtain a surveillance fix is on the order of a few seconds, the GPS signal turnaround option would be operationally viable. However, this option requires an improved aircraft avionics design (e.g., increased G/T and EIRP), a wideband channel in AEROSAT, and does complicate ASET and ASCC design.

6.3 IMPACT OF OPTIONS

This section discusses the impact of the options presented in Section 6.2 for the use of GPS in the AEROSAT Test and Evaluation Program.

The first option, using an "as-designed" GPS receiver, requires only minor hardware development for the AEROSAT T&E program. No modification of the AEROSAT avionics is required since the two systems would operate independently. The only interface required is between the GPS data processor and the AEROSAT data management subsystem (DMS). The DMS would format and transmit the surveillance data via an AEROSAT return channel.

Options 2 and 3 require AEROSAT avionics modification. Both options use the RF front end of the AEROSAT avionics and, hence, the design of the avionics must be sufficiently broadband to receive both GPS and AEROSAT frequency bands. The frequency plans for AEROSAT, MARISAT, and GPS are shown in Figure 19. As shown in the figure, the AEROSAT forward link frequency band does not overlap the GPS L_1 frequency band. Since it is common practice to design bandwidth limiting elements such as diplexers and filters to receive only the transmitted band to avoid interference, the GPS signals may be outside the normal receiption band of the avionics. The alternative is to require the design of the AEROSAT avionics RF front end to include the GPS signals. To receive the GPS C/A signal on L_1 the upper limit of the AEROSAT forward link band would have to be extended by about 5 MHz.

A second area of avionics modification involves the polarization of AEROSAT and GPS signals. The AEROSAT L-band forward link is currently left hand circular whereas the GPS signals are right hand circular. Figure 20 shows three types of implementation to receive both signals. The first implementation consists of broadband summing the AEROSAT and GPS signals. This approach results in a 3 dB loss in both the AEROSAT and GPS signals. The implementation shows the capability to switch out the

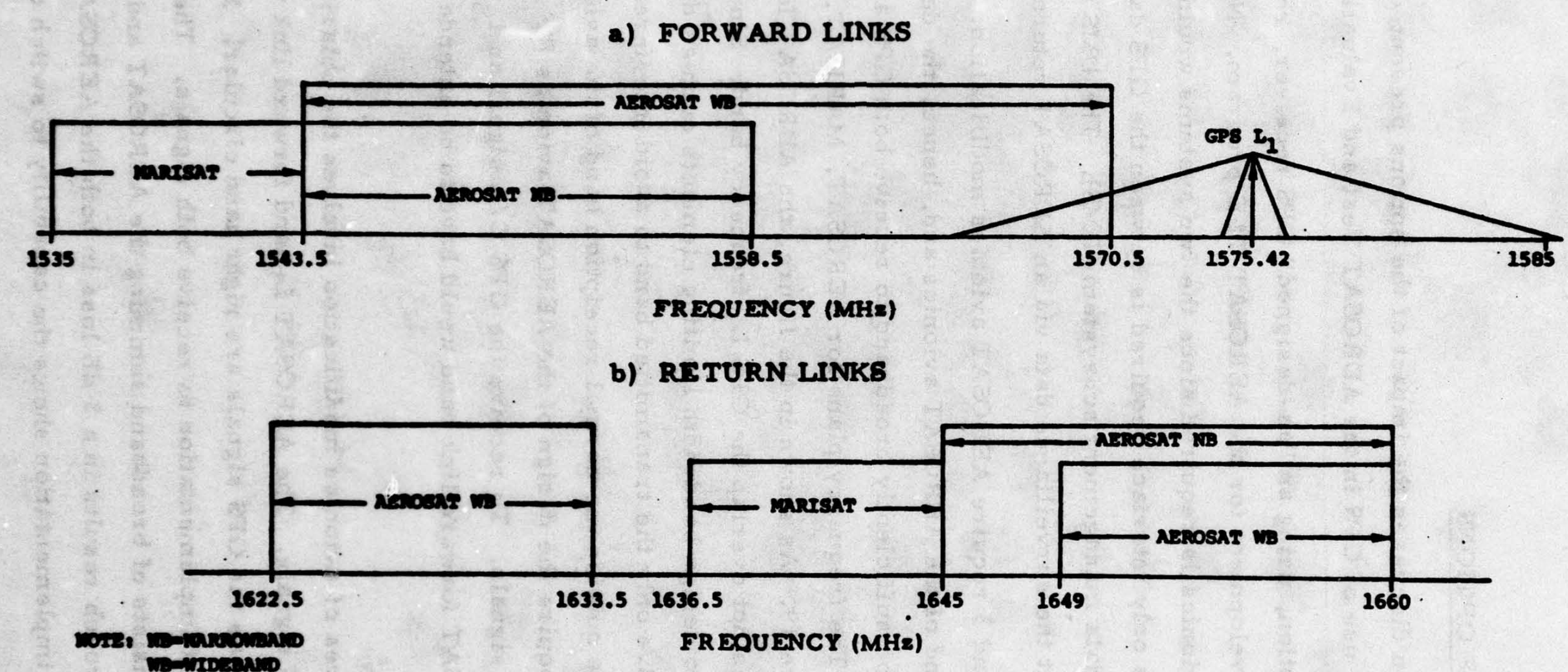


FIGURE 19. AEROSAT, MARISAT, AND GPS FREQUENCY PLANS

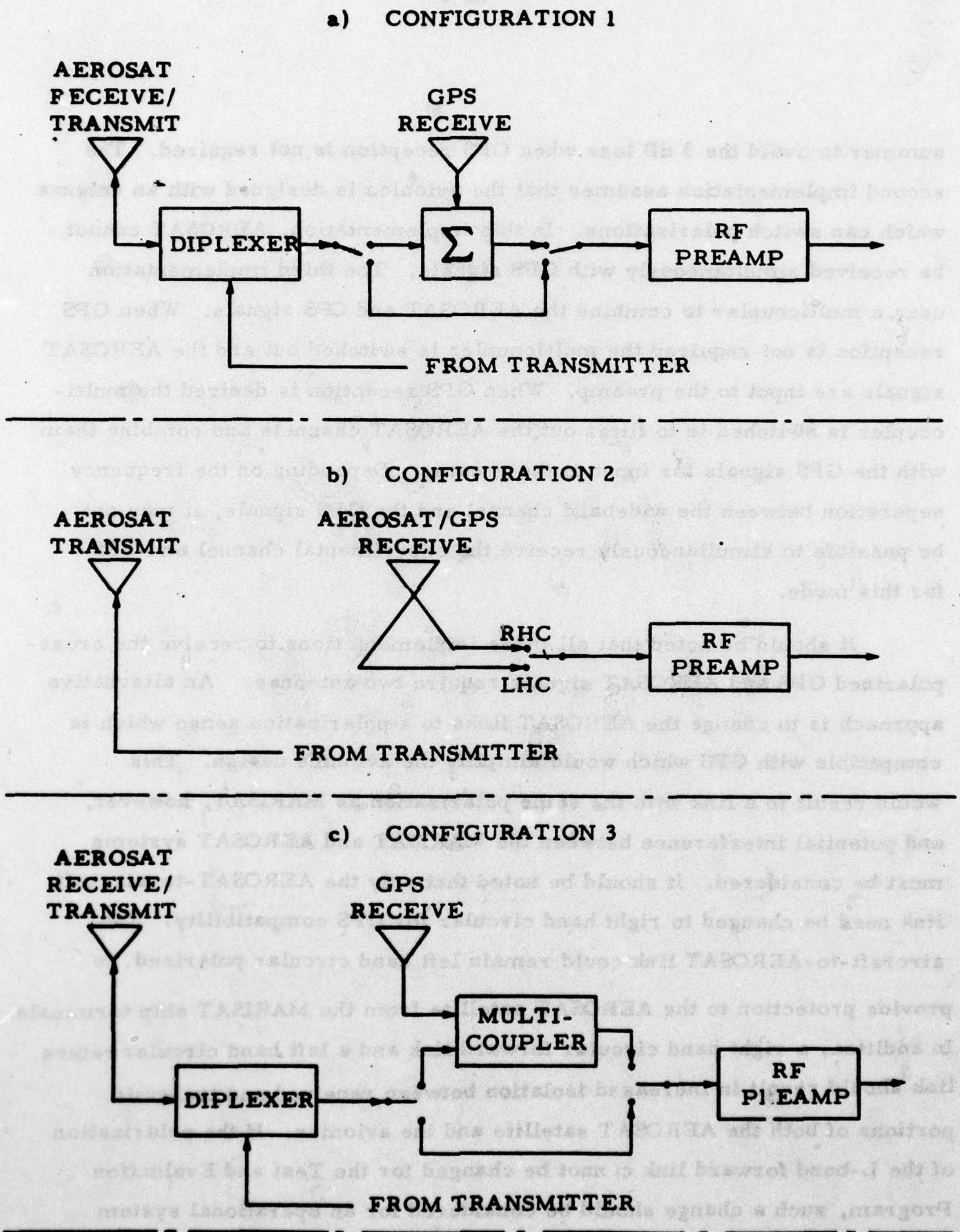


FIGURE 20. CONFIGURATIONS TO RECEIVE CROSS-POLARIZED AEROSAT AND GPS SIGNALS

summer to avoid the 3 dB loss when GPS reception is not required. The second implementation assumes that the avionics is designed with an antenna which can switch polarizations. In this implementation, AEROSAT cannot be received simultaneously with GPS signals. The third implementation uses a multicoupler to combine the AEROSAT and GPS signals. When GPS reception is not required the multicoupler is switched out and the AEROSAT signals are input to the preamp. When GPS reception is desired the multicoupler is switched in to filter out the AEROSAT channels and combine them with the GPS signals for input to the preamp. Depending on the frequency separation between the wideband channel and the GPS signals, it may not be possible to simultaneously receive the experimental channel and GPS for this mode.

It should be noted that all three implementations to receive the cross-polarized GPS and AEROSAT signals require two antennas. An alternative approach is to change the AEROSAT links to a polarization sense which is compatible with GPS which would simplify the avionics design. This would result in a link with the same polarization as MARISAT, however, and potential interference between the MARISAT and AEROSAT systems must be considered. It should be noted that only the AEROSAT-to-aircraft link need be changed to right hand circular for GPS compatibility. The aircraft-to-AEROSAT link could remain left hand circular polarized, to provide protection to the AEROSAT satellite from the MARISAT ship terminals. In addition, a right hand circular forward link and a left hand circular return link should result in increased isolation between received and transmit portions of both the AEROSAT satellite and the avionics. If the polarization of the L-band forward link cannot be changed for the Test and Evaluation Program, such a change should be considered for an operational system if GPS operation is required. The remainder of this section assumes that the RF portions of the avionics could be made to be compatible with GPS by one of the approaches given above.

The impact of the GPS signal processor (Option 2) on the avionics design below the 70 MHz IF is dependent on the method of implementation and, hence, cannot be fully specified here. In general, the signal processor will contain processing loops to track GPS signal carriers and codes. The operation of the loops and the measurement of pseudorange would probably be controlled by a microprocessor which interfaces with the DMS. The DMS would perform the navigational computations based on input from the GPS signal processor and control the transmission of surveillance data to air traffic control via AEROSAT. The computer resources and software required in the DMS cannot be specified at this time. A current estimate of the computer memory requirements for the data processor of the GPS Z-class receiver is 8 K of 16 bit words.

An improved avionics design is required to make Option 3 (GPS signal turnaround) feasible. The AEROSAT reference avionics do not provide sufficient link quality for GPS receiver operation. The typical improvement required is a 6 dB increase in both avionics G/T and EIRP. This improved avionics performance and RF front end commonality requirement necessitates a major avionics re-design at best and may require a totally new avionics design. The required avionics design and resulting impact to the AEROSAT program are beyond the scope of this report. As a result, the evaluation of Option 3 as a part of the AEROSAT T&E Program was not considered further.

7. GPS SYSTEM PERFORMANCE

The position determination performance of the Global Position System is a function of satellite location errors, satellite-to-user range measurement errors including both receiver measurement and propagation errors, and satellites/user geometry. The combined effect of all errors are, in general, lumped into two performance parameters; User Equivalent Ranging Error (UERE), and Geometrical Dilution of Precision (GDOP). UERE is the combination of all system range measurement errors. This quantity includes satellite position error which, although not strictly a ranging error, is treated as such. GDOP is a measure of the geometrical performance of the system and is defined such that when GDOP is multiplied by UERE the position determination accuracy is obtained. Formally, GDOP is the resultant 1σ error in user position for a given satellite configuration, assuming perfect knowledge of satellite position and uncorrelated unity 1σ errors in each of the four pseudo-range measurements.

This section will discuss the error sources which constitute the UERE and present estimates of their magnitudes. For errors which are dependent on receiver implementation, a Clear Signal Set is assumed. Here a Clear Signal Set is defined as a generic GPS receiver which uses only the C/A navigation signal on L_1. Although a specific design is not given, the Clear Signal Set would be functionally similar to the Z-class GPS receiver.

This section also presents a technique for synchronizing ASETs to system time provided by GPS. Two methods of time synchronization are described and th : timing performance is indicated.

The final portion of the section addresses the coverage and GDOP values of the GPS system. Since the AEROSAT Program spans both the Phase II and Phase III GPS orbital configurations, both cases are presented.

The GDOP factors which are used to describe the geometrical performance of the system are defined as:

HDOP = Horizontal Dilution of Precision

VDOP = Vertical Dilution of Precision

TDOP = Time Dilution of Precision

The factors are defined such that, when multiplied by UERE, the resultant is the accuracy in the horizontal plane, vertical direction, and timing, respectively.

7.1 USER EQUIVALENT RANGING ERROR (UERE)

The parameters which constitute the UERE are the satellite ephemeris error, the atmospheric effects on the ranging signal, the satellite timing error, the receiver noise and resolution errors in measuring time-of-arrival, and the receiver multipath induced error. The uncorrelated portion of these errors are root-sum-squared to form UERE. While the satellite position errors are not, strictly speaking, a ranging error, it is found convenient to treat them as such. The resultant artifact of combining all system measurement errors into one quantity, which is then multiplied by a GDOP factor, has been termed a "User Equivalent Ranging Error."

Satellite ephermeris error is the difference in actual satellite position compared to the position computed by the User using the provided System Data. There are many sources for this error, including incomplete modeling of the earth's force field, staleness of the data sent to the User, truncation of that data format, etc. For GPS Phases II and III, the statistic that has been derived over time-space for this component of UERE is 5 ft. (1σ) (Ref. 2).

Atmospheric errors include the effects of the ionosphere and troposphere, with the former being the prime contributor. Delays of EM waves

through the ionosphere can be very large, sometimes exceeding 300 nsecs at 1600 MHz during daylight hours. This translates directly into an error in time-of-arrival and is equivalent to an apparent range error. The GPS usually employs two ways to compensate for this error. In the first, another synchronized EM wave is transmitted at a different frequency and the difference in time-of-arrival noted. A straightforward calculation then allows determination of the ionospheric delay. In the second technique, the ionospheric delay is modeled as a function of approximate User location, time-of-day, season, etc. The first method is very accurate, but expensive. The second is less expensive but requires update of the model coefficients with data received on the 50 bps data stream. In the interest of economy, both in hardware and software, the Clear Signal Sets will not utilize either technique to correct for ionospheric delay, but rather will use a fixed correction. In addition, a simple and accurate model for troposheric error correction is included. The resultant net error for this category is conservatively estimated at 20 ft (1σ) (Ref. 10).

The term "Satellite Timing Error" is applied to the uncertainty in signal delay due to both the satellite unmodeled clock drift and an uncalibrated portion of the receiver channel. A value of 3 ft (1σ) for this error is supported by numerous GPS equipment tests.

As mentioned earlier, the receiver "ranging" process is really a time-of-arrival measurement. The jitter in this observation caused by receiver terminal noise, for a nominal clear-signal C/N_o of 35 db-Hz and a delay-lock loop bandwidth (B_L) of 1.0 Hz is approximately

$$\sigma_R = \Delta \sqrt{\frac{B_L N_o}{2C}}$$

$$\sigma_R = 13 \text{ ft.}$$

where

Δ = range equivalent of one C/A code chip

$\cong$ 1000 ft.

The resolution of the readout is specified at 1/64 of a chip or about 16 ft., producing a standard deviation of

$$\sigma_P = \frac{16}{\sqrt{12}} = 4.6 \text{ ft.}$$

The RSS of these two quantities results in a receiver measurement error of 13.8 ft. (1σ).

The last error of interest is that induced by receiver multipath effects. It is well known that spread spectrum signals considerably mitigate this phenomenon, since PN receivers do not respond to signals delayed by more than 1.5 chips. For the GPS Clear-Signal of nominally 1 MHz chipping-rate, this corresponds to 1500 ft. An aircraft receiving a signal at 5° elevation angle (the worst case) could not experience multipath off the ground or water delayed by less than 1500 ft. unless he were at an altitude of 9000 ft. or less. Since for most cases of interest (over-ocean flights) altitudes will greatly exceed this, ground-multipath error is not included here in UERE.

Multipath may also be caused by reflections off the aircraft. However, if the antenna is mounted on the fuselage surface, as postulated in this study, reflections can only be reasonably expected off the tail. Since the combined probabilities of correct satellite orientation, exact ray geometry, appreciable reflected power, and significant antenna gain rule against many occurrences of multipath for that case, localized multipath error is also discounted.

Table XII summarizes the component errors of UERE. The RSS total is the value used in this report for all Phase III analysis of the GPS Clear-Signal Set performance.

Table XII. GPS Phase III Equivalent Error

Satellite Ephemeris Error	5 (ft)
Atmospheric Error	20
Satellite Timing Error	3
Receiver Measurement Error	13.8
Multipath Error	nil
UERE (RSS)	25 ft (1σ)
(NOTE: Above values applicable only to AEROSAT Clear-Signal application)	

7.2 ASET TIME TRANSFER ERROR

An ASET may be time synchronized in two ways. In Phase II a Clear-Signal User Set may be used to pseudo-range to one satellite, which, with knowledge of satellite position and surveyed ASET location, allows determination of GPS time. In Phase III that User Set may be used to track four satellites in the normal way leading directly to synchronization of local time. As shown below, the accuracies of these two techniques are roughly the same. The assumption made in both cases is that moderately directive antennas are employed in tracking the satellites to avoid multipath errors.

In the single satellite measurement, the total error in determining local time is the error in measuring time-of-arrival added to the error in knowledge of range to the satellite. (The equivalence of 1 ft. = 1 nsec is used here in referring to range error.) Since uncertainty in satellite position has already been folded into UERE, the only additional error is ASET

location uncertainty. A conservative estimate of that survey error is 31 ft. (99% confidence) (Ref. 11). The Phase II time transfer error, then, consists of approximately a 31 nsec ASET location bias and a 25 nsec (1σ) random component due to GPS measurements.

In the multiple satellite measurement technique, the total error is simply the UERE multiplied by the TDOP applicable at the time of measurement. As shown in the next section, TDOP will not exceed approximately 2.4 in the Phase III configuration. The time transfer error, then, never exceeds about 60 nsec (1σ).

7.3 PHASE II PERFORMANCE

7.3.1 PHASE II SATELLITE COVERAGE

The geographical area addressed in this study is the Atlantic Region, defined as that area from 40° East to 90° West longitudes, and from 40° South to 70° North latitudes. It includes all of Europe, half of the U.S., and nearly all of Africa and South America.

The orbital parameters of the GPS Phase II deployment that were used in the analyses are listed in Table XIII. Because satellite geometries; as seen from any point on the earth, repeat at eight hour intervals, it is only necessary to examine that limited span of time when generating availability or GDOP statistics.

Figures 21 through 24, as examples of Phase II coverage, indicate those regions in the stated area of interest where three or more satellites are in view at arbitrarily defined times, t = 0, 2, 4, and 6 hours. Figure 25 is a computer printout showing the exact number of satellites visible to any point at t = 0. Note the very limited region where four satellites are visible. This scarcity of four satellite coverage is true at all times in Phase II. Averaged over all time and all points in the region of interest, the availability of four satellites is only 5%.

Of more interest is the availability of at least three satellites in the region of interest, since three satellite coverage together with altimeter data allows the solution for User location and time synchronization. Figure 26 shows the availability of at least three satellites as a function of latitutde. The average in the region of interest is 58%.

Figure 21 through 26 are based on a minimum user elevation angle of 10°.

TABLE XIII. GPS PHASE II - 3 x 3 ORBITAL CHARACTERISTICS

Satellite Ident	Ecc (e)	Inc (i)	A of P (ω)	RA (Ω)	PER (T)	MA (M)
1	0	63	0	0	12	0
2	0	63	0	0	12	120
3	0	63	0	0	12	240
4	0	63	0	120	12	0
5	0	63	0	120	12	120
6	0	63	0	120	12	240
7	0	63	0	240	12	0
8	0	63	0	240	12	120
9	0	63	0	240	12	240

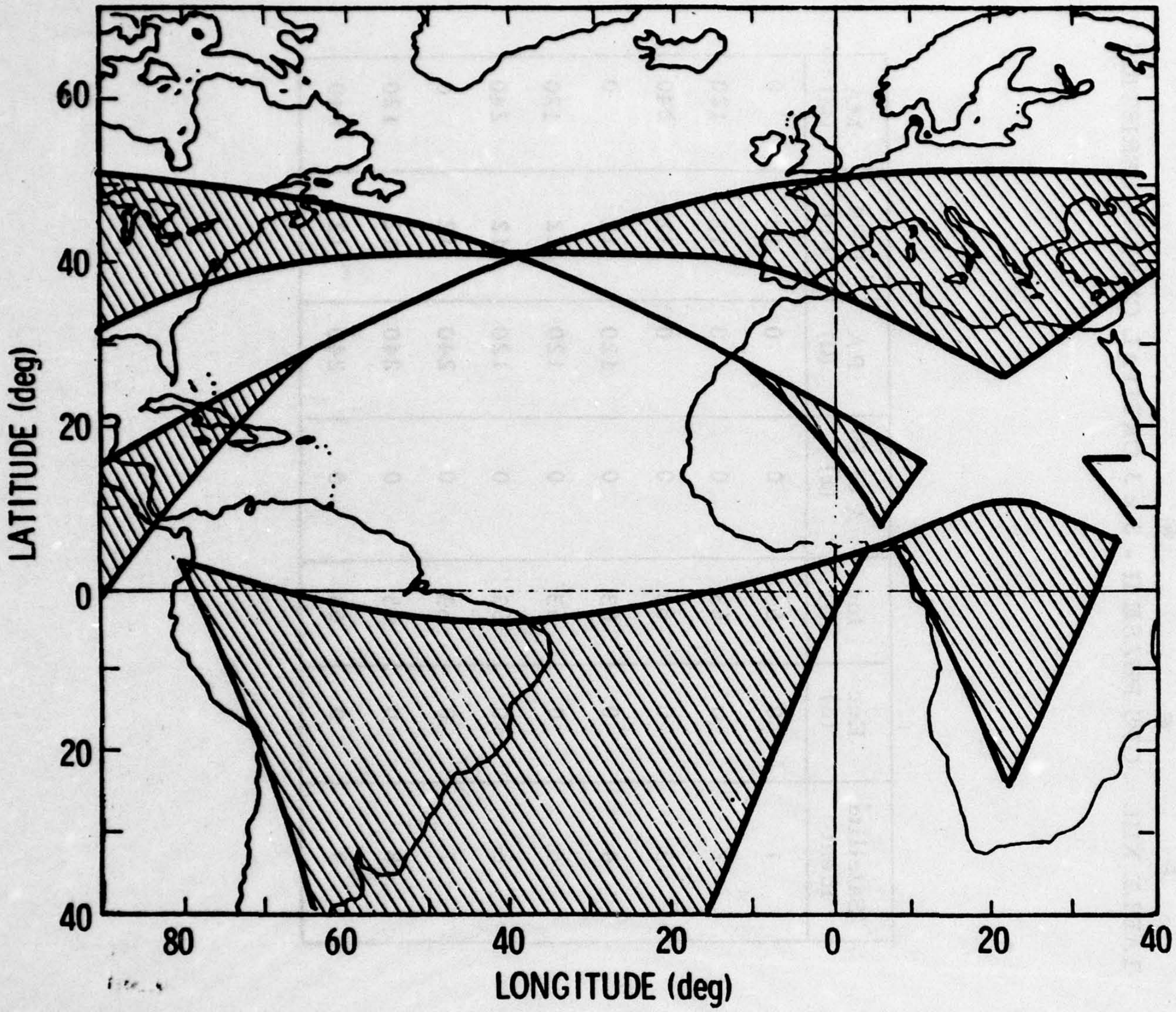


Figure 21. Three or More Satellites in View (Clear Areas) at Arbitrary Time T = 0 hours (Phase II)

AD-A069 037 AEROSPACE CORP WASHINGTON D C F/G 17/7
APPLICATION OF THE GLOBAL POSITIONING SYSTEM (GPS) TO THE AEROS--ETC(U)
MAY 76 T L EDWARDS DOT-FA71WA-2577
UNCLASSIFIED 76-3 FAA-RD-76-142 NL

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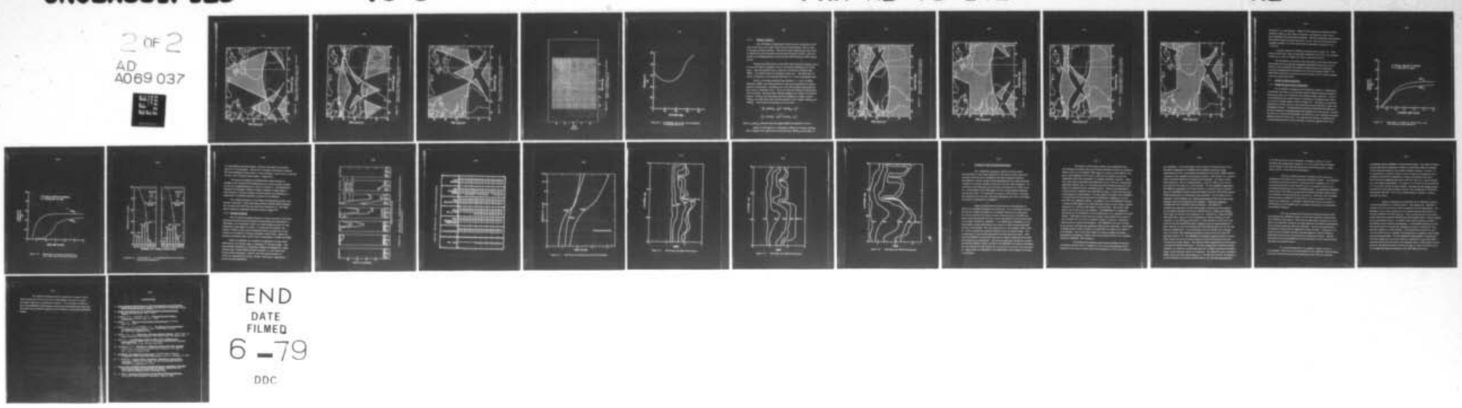

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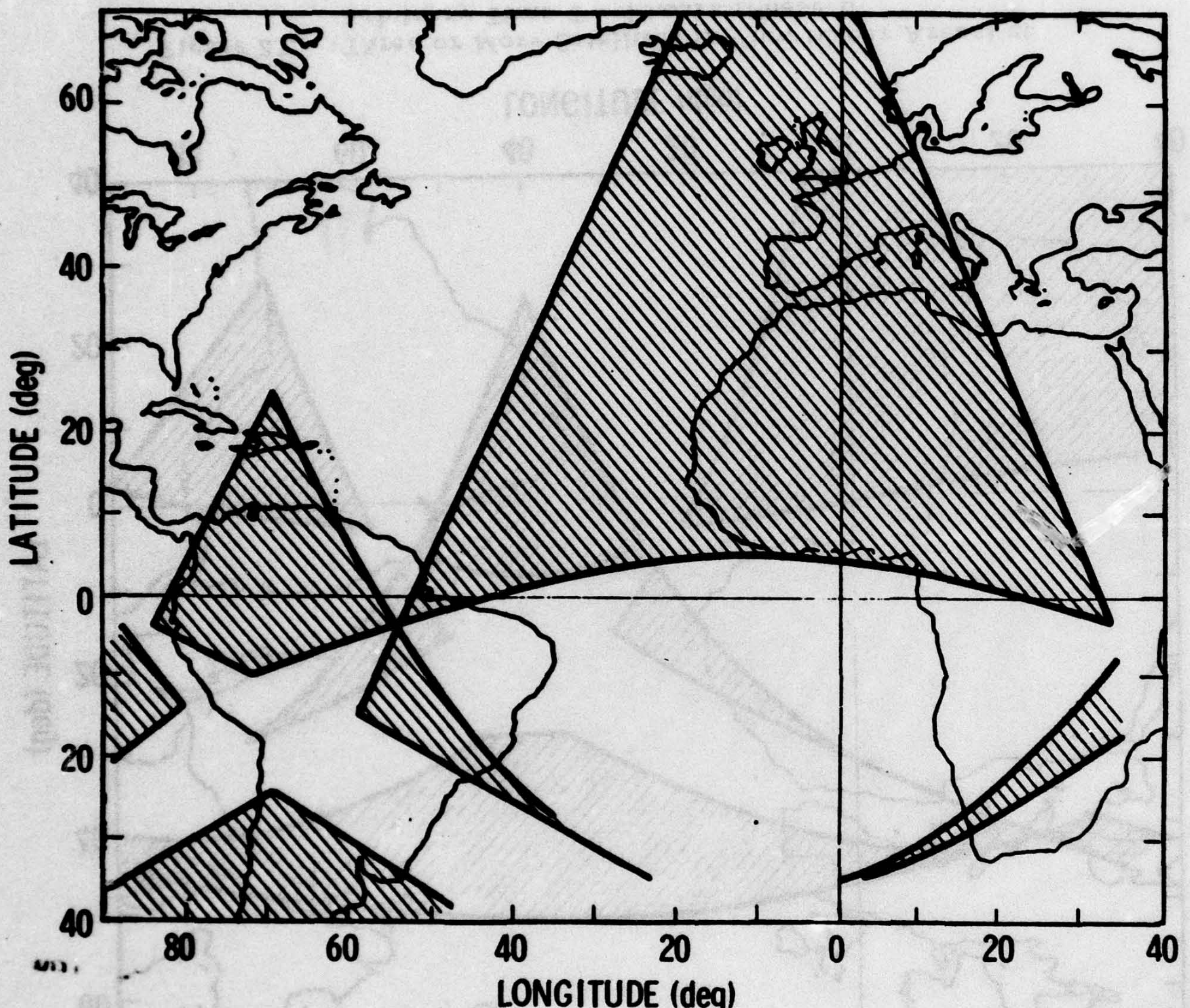

Figure 22. Three or More Satellites in View (Clear Areas) at Arbitrary Time T = 2 hours (Phase II)

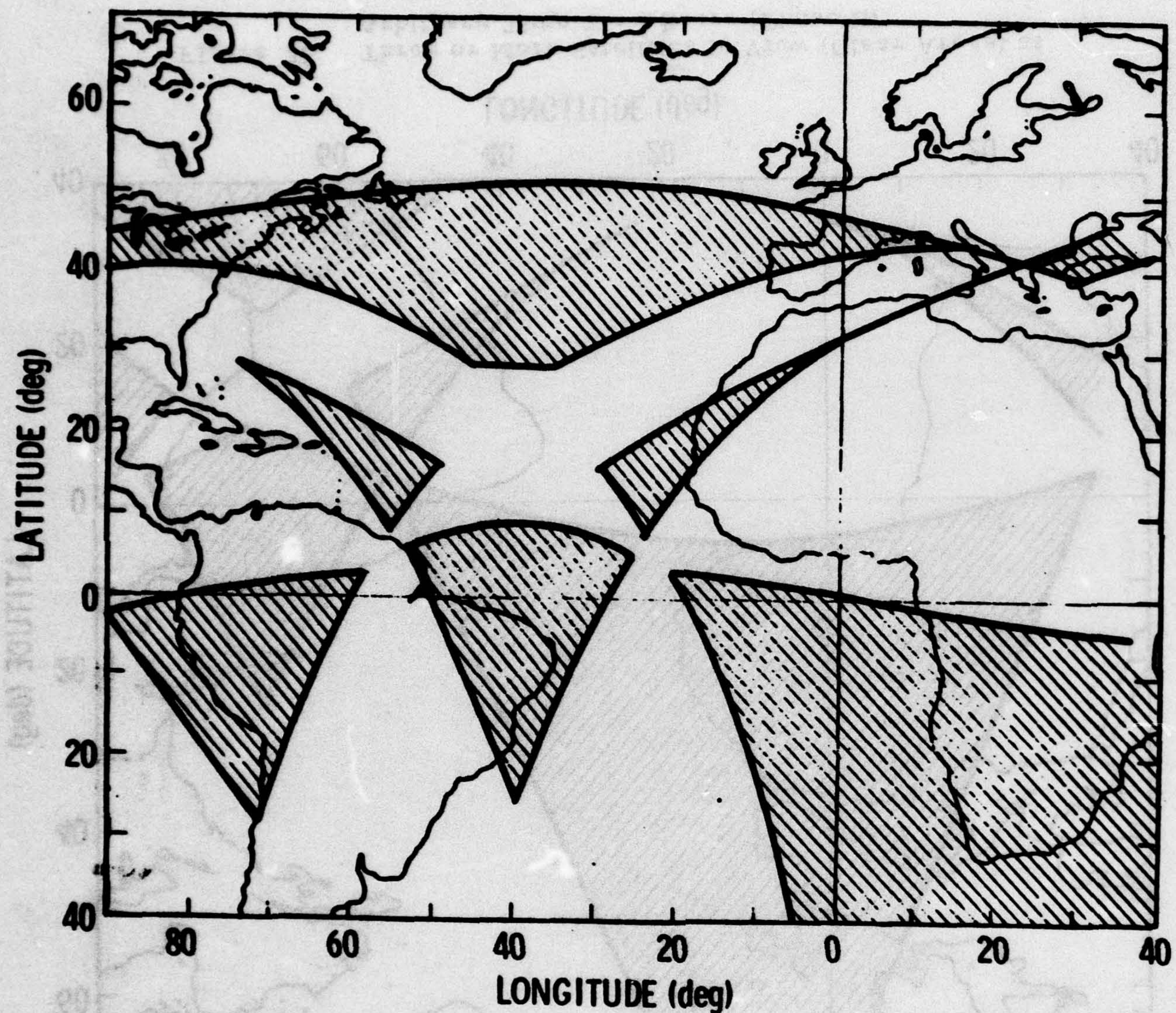

Figure 23. Three or More Satellites in View (Clear Areas) at Arbitrary Time T = 4 hours (Phase II)

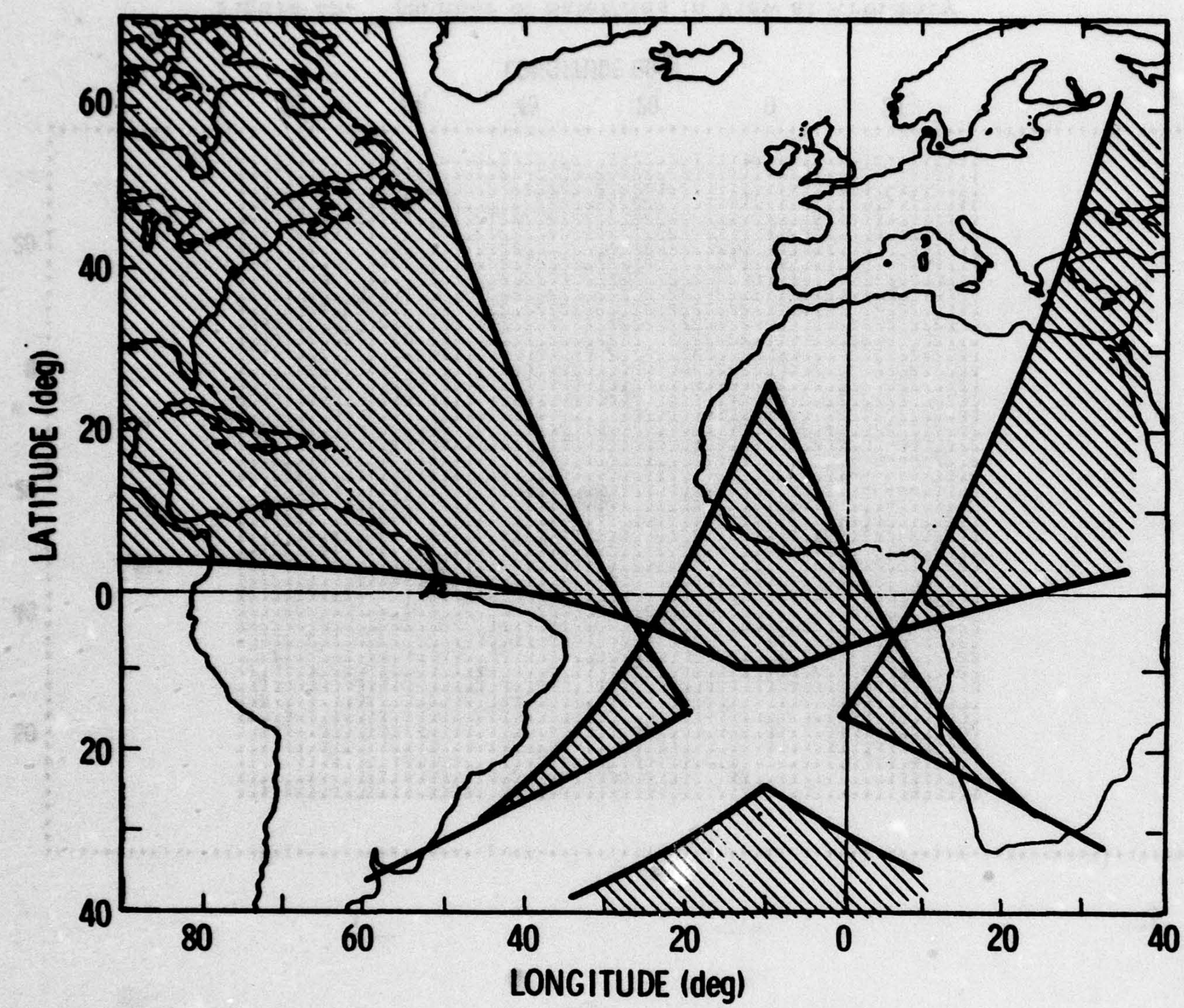

Figure 24. Three or More Satellites in View (Clear Areas) at Arbitrary Time T = 6 hours (Phase II)

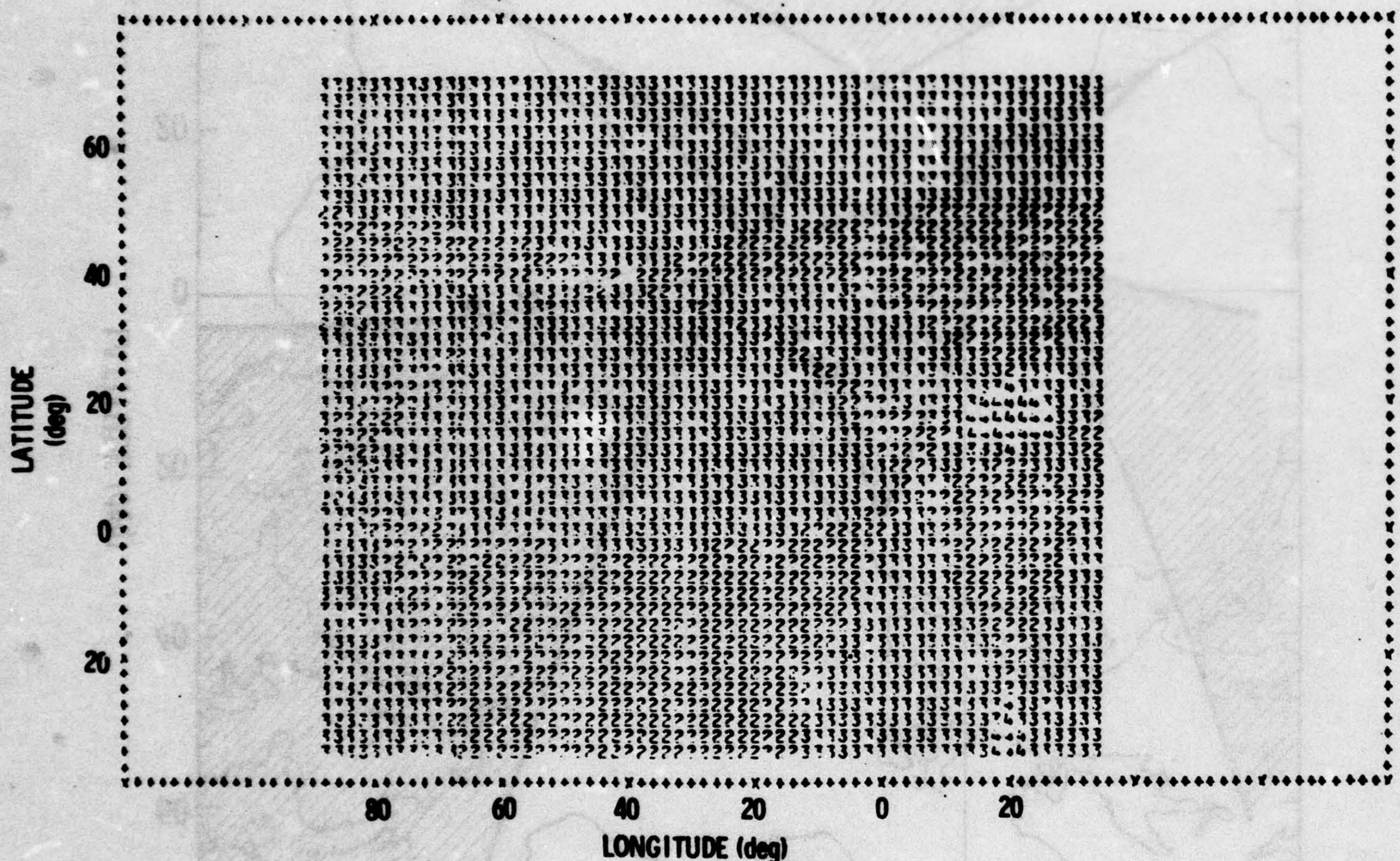

Figure 25. Number of Satellites in View at Arbitrary Time T = 0 hours (Phase II)

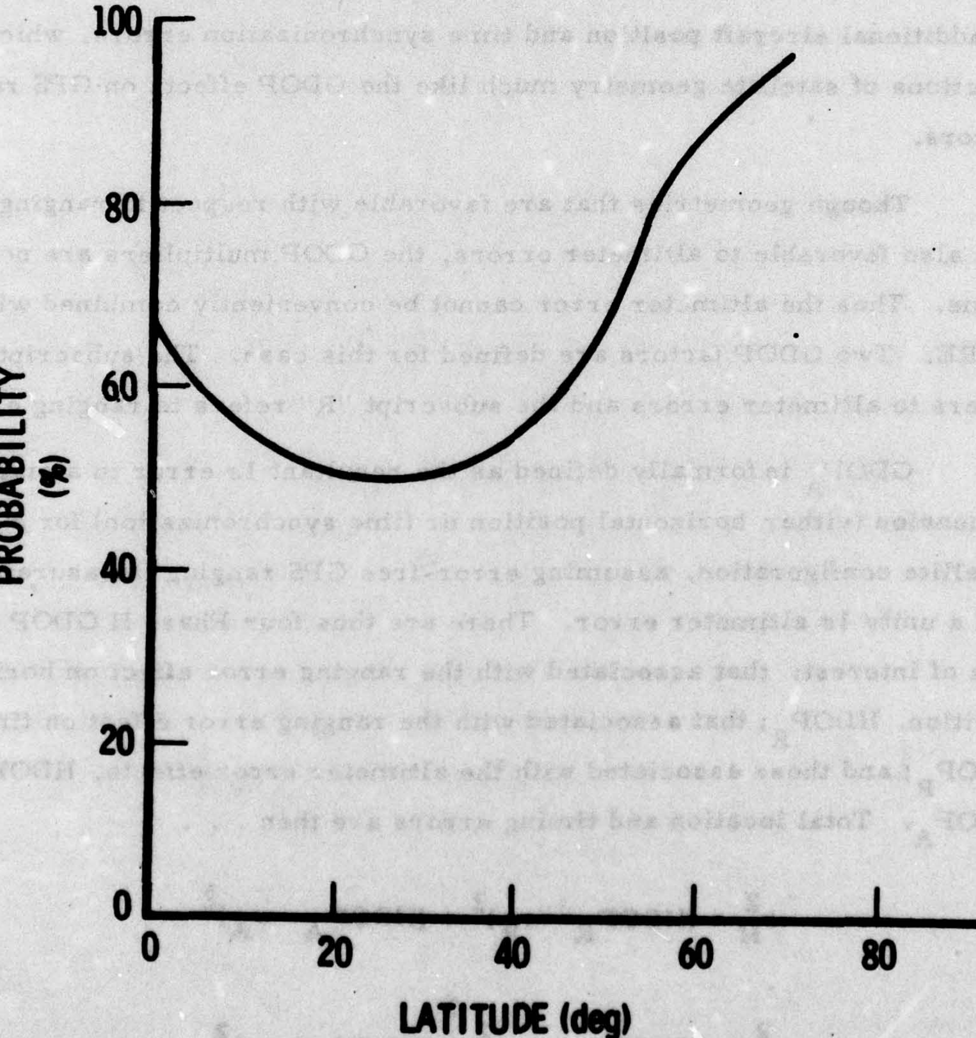

Figure 26. Probability of at Least Three Satellites vs Latitude (Phase II)

7.3.2 PHASE II GDOP'S

The GPS Phase II deployment, with only three satellites in view most of the time, will require the use of aircraft altimeter data in order to calculate position and time. The error in this measurement will result in additional aircraft position and time synchronization errors, which are functions of satellite geometry much like the GDOP effects on GPS ranging errors.

Though geometries that are favorable with respect to ranging errors are also favorable to altimeter errors, the GDOP multipliers are not the same. Thus the altimeter error cannot be conveniently combined with UERE. Two GDOP factors are defined for this case. The subscript "A" refers to altimeter errors and the subscript "R" refers to ranging errors.

$GDOP_A$ is formally defined as the resultant 1σ error in a stated dimension (either horizontal position or time synchronization) for a given satellite configuration, assuming error-free GPS ranging measurements, and a unity 1σ altimeter error. There are thus four Phase II GDOP quantities of interest: that associated with the ranging error effect on horizontal position, $HDOP_R$; that associated with the ranging error effect on time, $TDOP_R$; and those associated with the altimeter error effects, $HDOP_A$ and $TDOP_A$. Total location and timing errors are then . . .

$$\sigma_H^2 = (HDOP_R \cdot \sigma_R)^2 + (HDOP_A \cdot \sigma_A)^2$$

$$\sigma_T^2 = (TDOP_R \cdot \sigma_R)^2 + (TDOP_A \cdot \sigma_A)^2$$

where σ_R and σ_A represent the one-sigma UERE and altimeter errors.

Figures 27 through 30, as examples of Phase II coverage, indicate those regions in the stated area of interest where $HDOP_A$ is less than 1.5

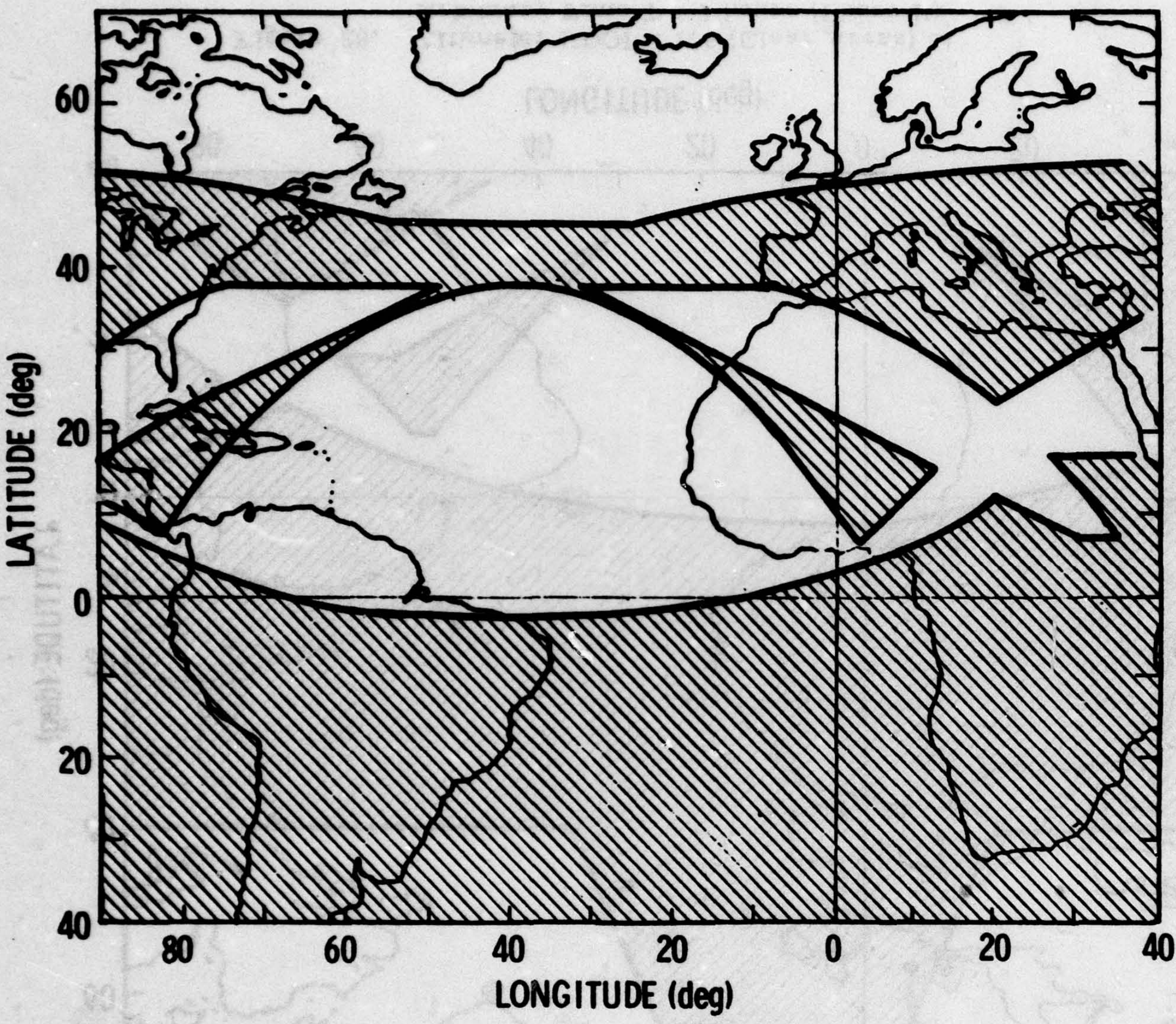

Figure 27. Altimeter HDOP < 1.5 (Clear Areas) at Arbitrary Time T = 0 hours (Phase II)

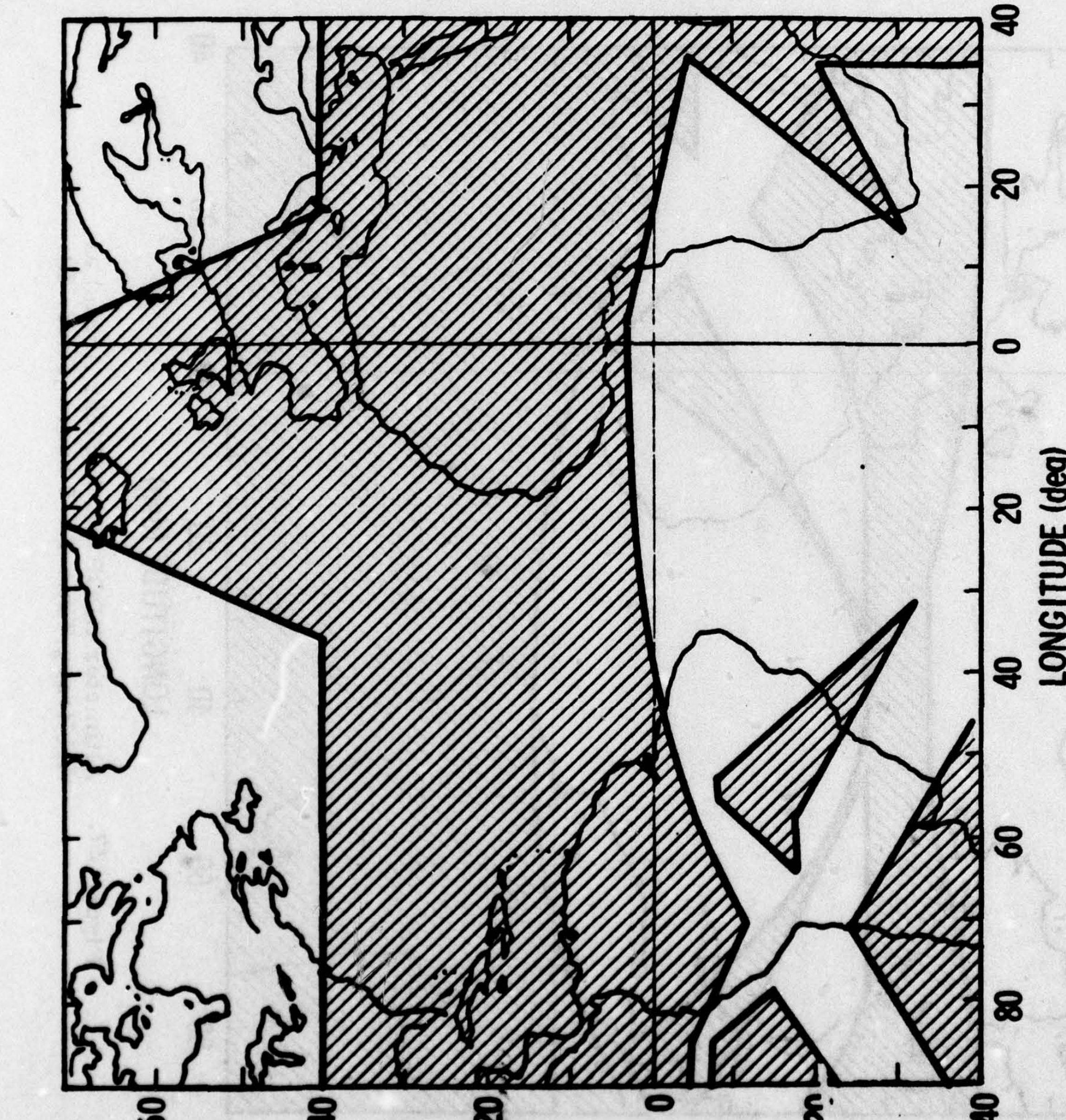

Figure 28. Altimeter HDOP $<$ 1.5 (Clear Areas) at Arbitrary Time T = 2 hours (Phase II)

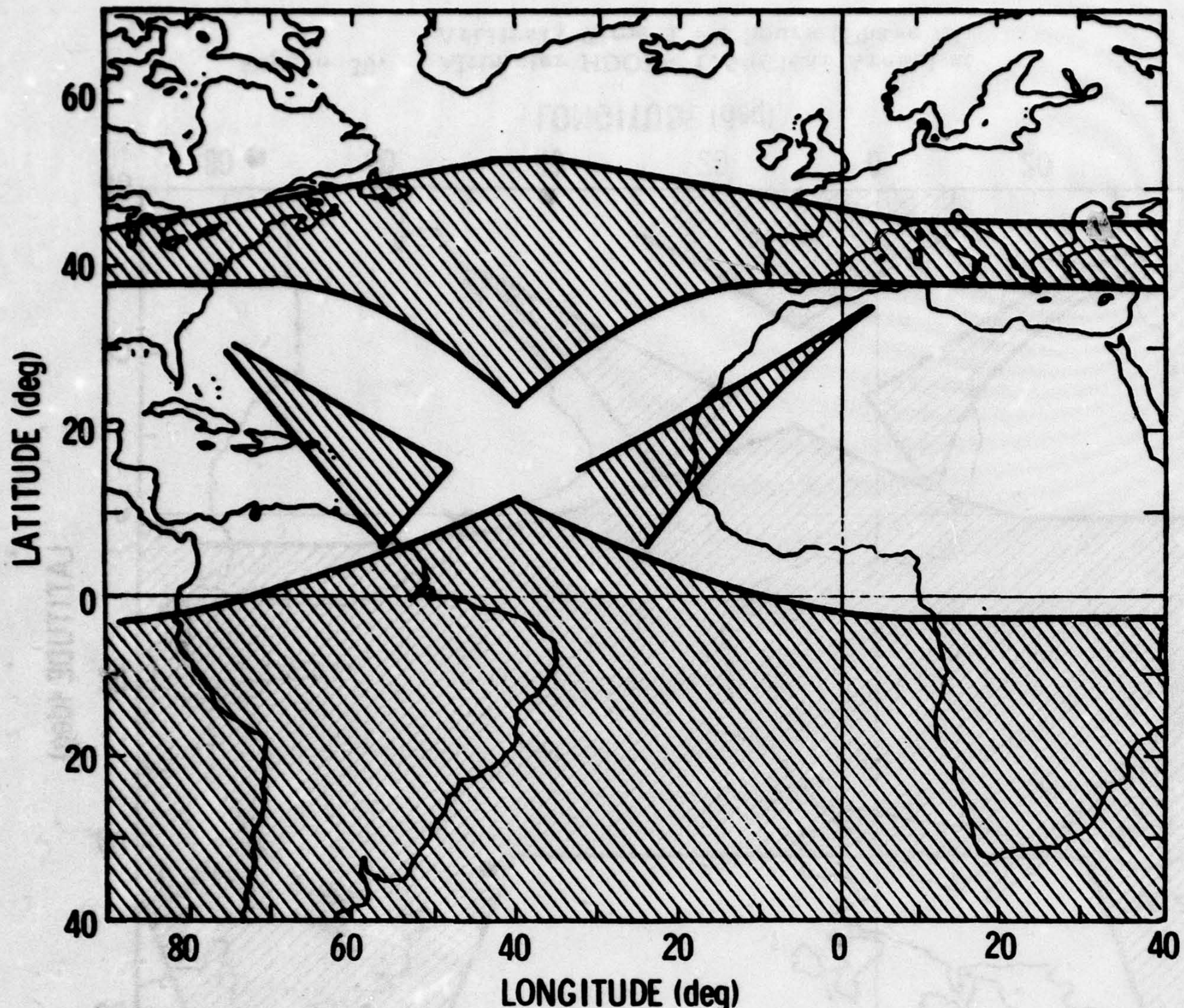

Figure 29. Altimeter HDOP < 1.5 (Clear Areas) at Arbitrary Time T = 4 hours (Phase II)

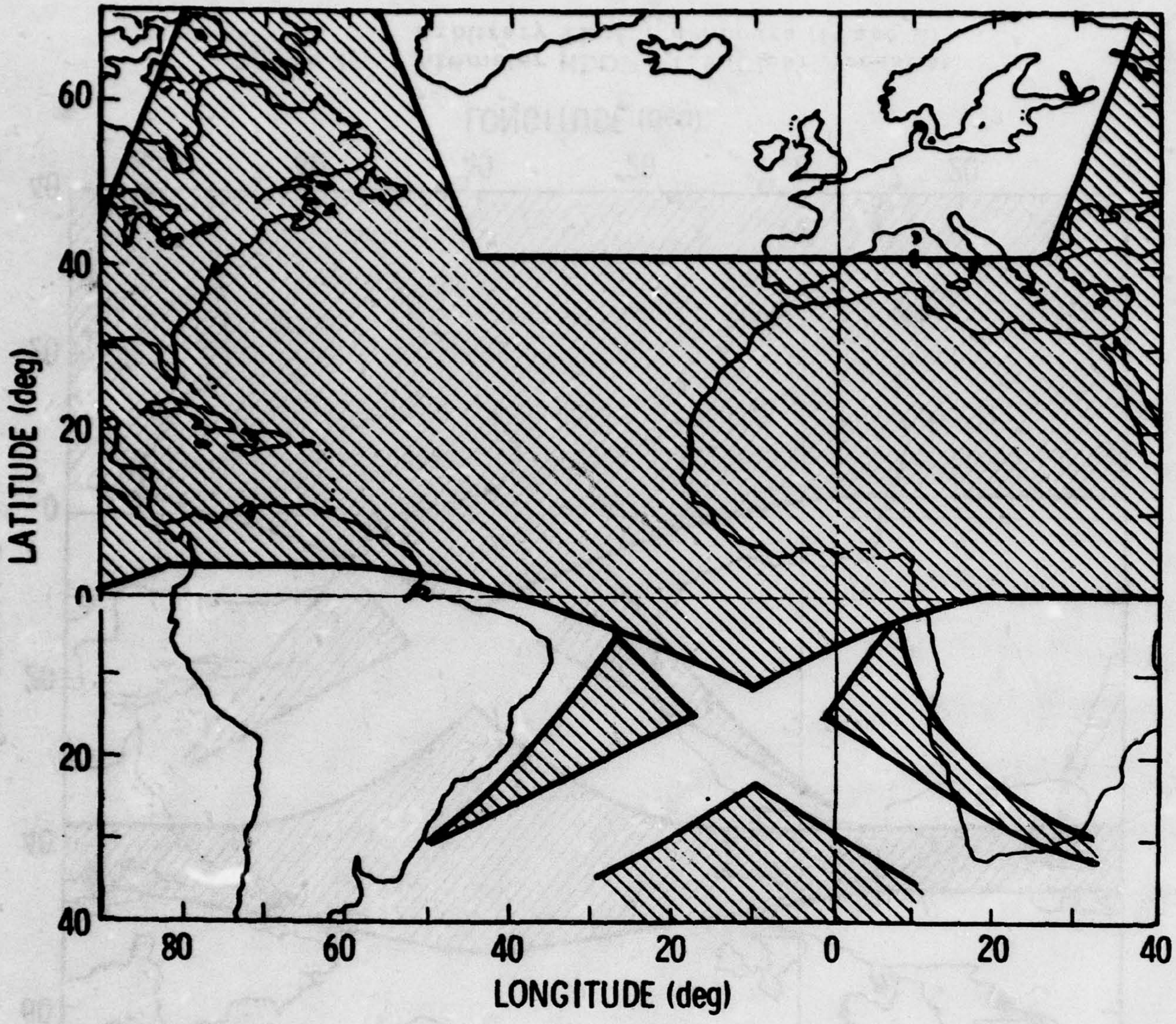

Figure 30. Altimeter HDOP < 1.5 (Clear Areas) at Arbitrary Time T = 6 hours (Phase II)

at times 0, 2, 4 and 6 hours. Figure 31 then shows the cumulative probabilities of $GDOP_A$ in the region of interest, averaged over time, given the availability of at least three satellites. Note the significant uncertainities that will be caused by typical altimeter errors: only 5% of the time is the resultant location error less than 60 feet, assuming an altimeter error of 300 feet.

A similar analysis of $GDOP_R$ is summarized in Figure 32. Fifty percent of the time, when at least three satellites are in view, the resultant location error due to a UERE of 25 feet is less than 150 feet.

The conclusion to be drawn from these data is that Phase II location and timing errors are almost completely controlled by altimeter errors. Whenever three satellites are visible, location accuracy is estimated merely by multiplying the altimeter error by its associated GDOP. The GPS UERE would have to increase by about a factor of five before it begins to have an appreciable effect.

7.4 PHASE III PERFORMANCE

7.4.1 PHASE III SATELLITE COVERAGE

The 24 satellite configuration for Phase III results in a distribution of satellites such that a user may determine his three dimensional position and system time on a worldwide basis without using an altimeter. The percent probability that a given number of satellites is simultaneously visible to a user on a global basis is shown in Figure 33. The users are uniformly distributed over the surface of the earth and the observations are uniformly distributed in time. The distribution includes all satellite observations for all user longitude and latitude positions throughout the orbit period. Because the users are uniformly distributed, the number at a given latitude decreases with the cosine of the latitude. It is seen that the number of satellites observed simultaneously is never less than 6 and never greater than 11 for

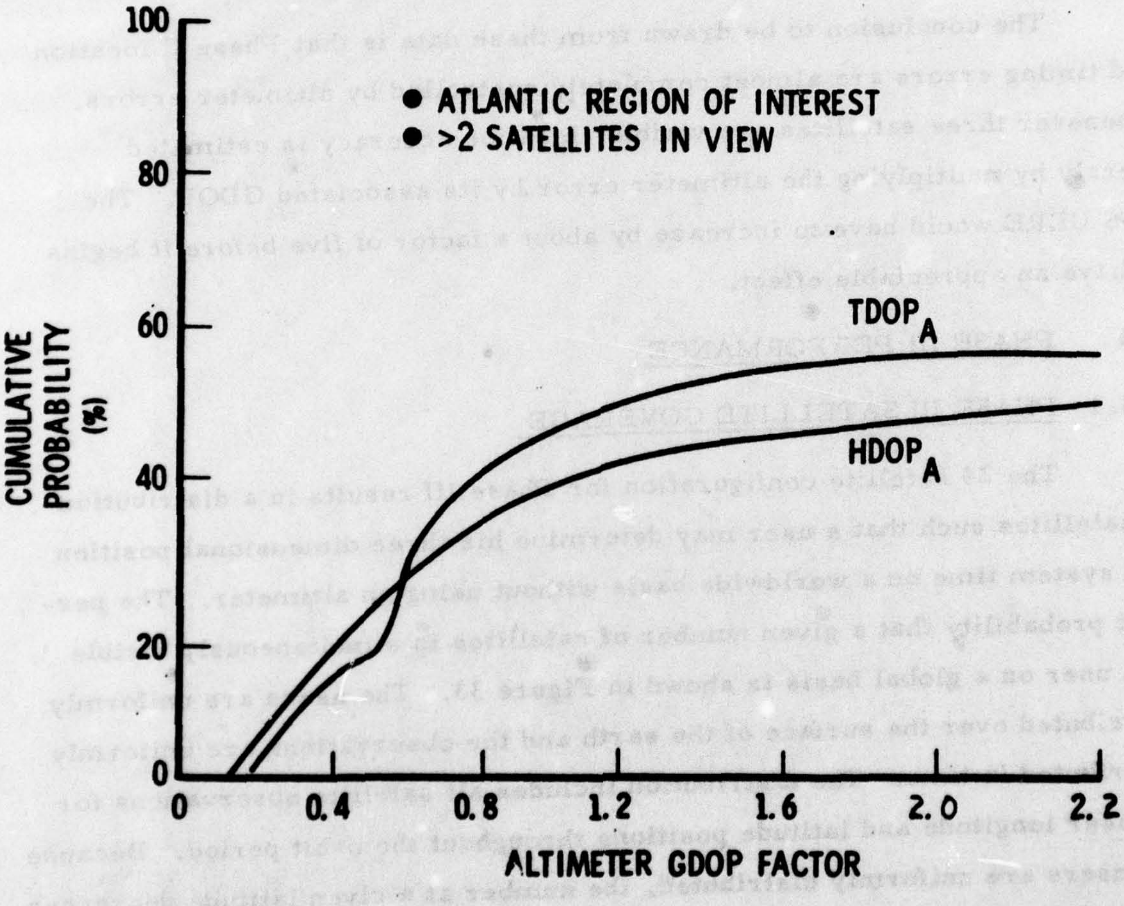

Figure 31 **Probability of Altimeter GDOP Factor Less Than Abscissa Value (Phase II)**

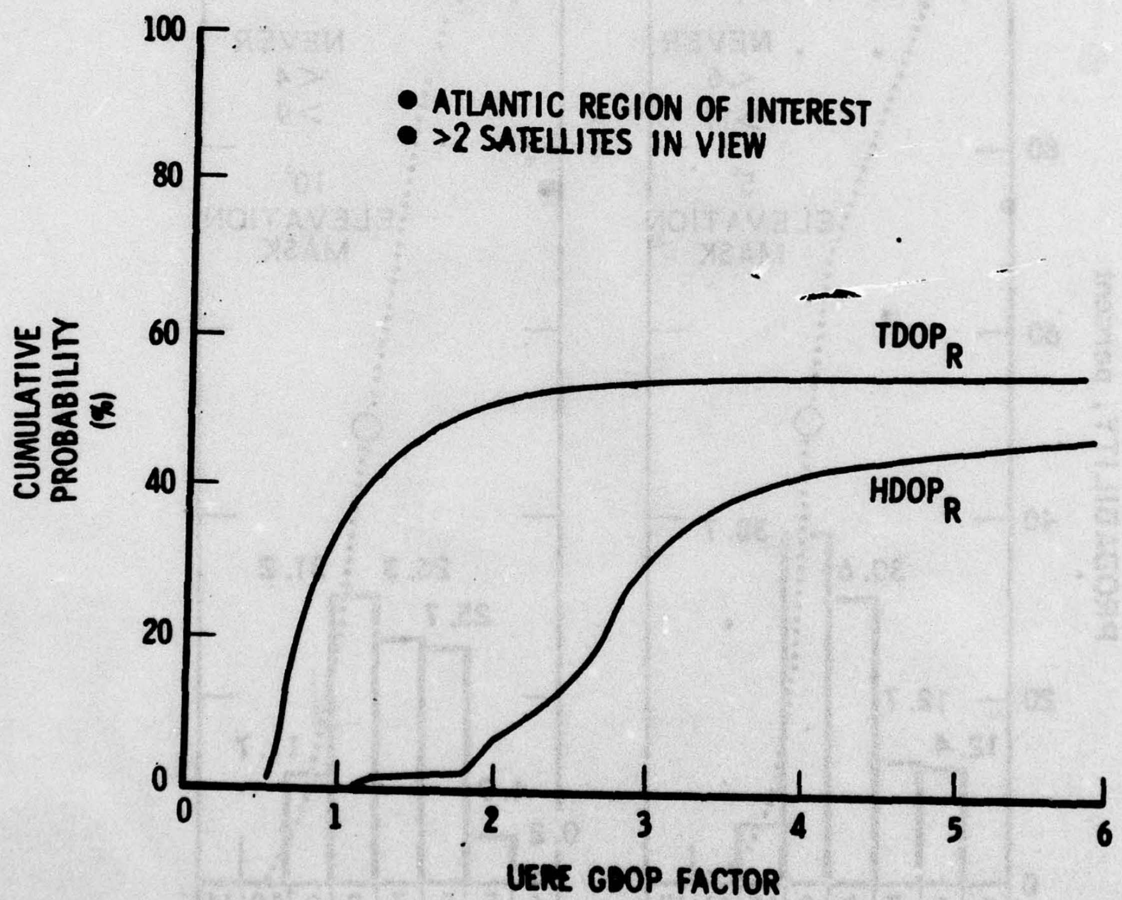

Figure 32. Probability of Ranging GDOP Factor Less Than Abscissa Value (Phase II)

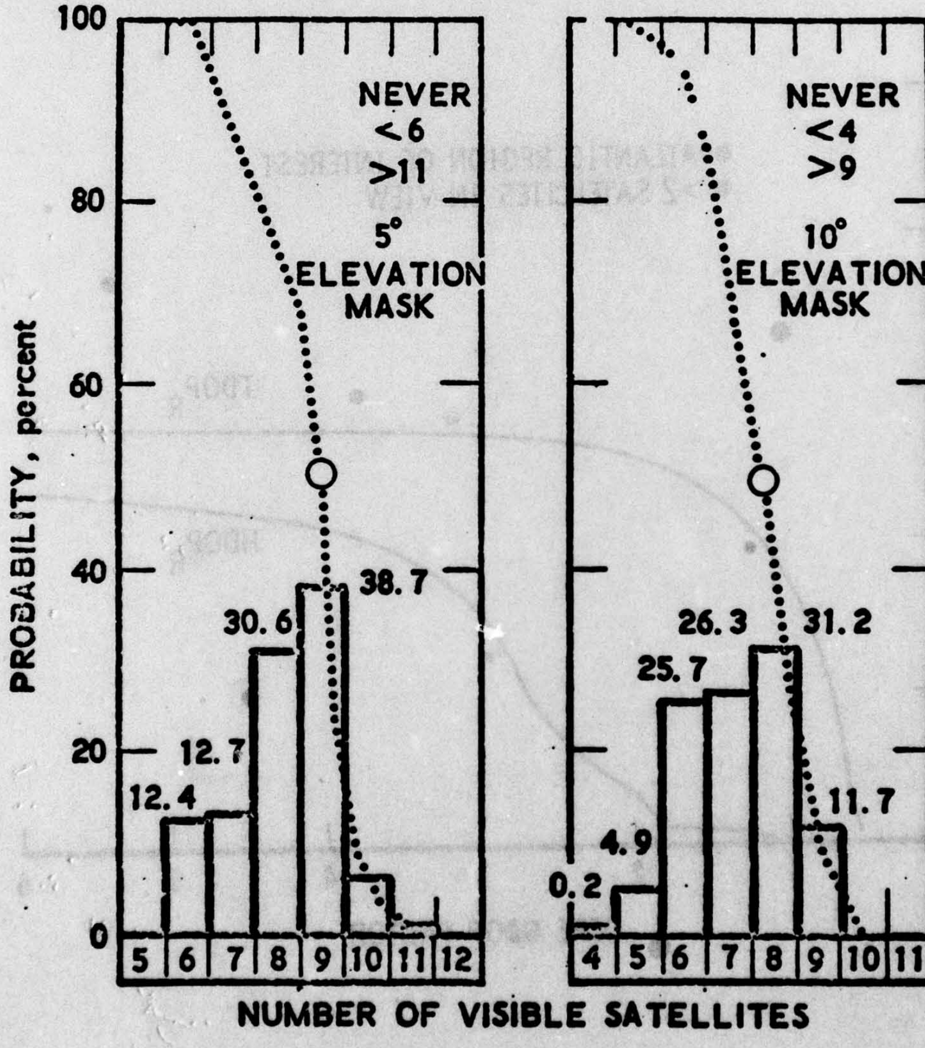

FIGURE 33. GPS PHASE III - 3 X 8 DISTRIBUTION OF GLOBAL SATELLITE VISIBILITY

a 5-deg masking (elevation) angle, and never less than 4 nor greater than 9 for a 10-deg angle. The percent cumulative distribution indicates that the probability of observing 9 or more satellites is 44.3 and 11.7 percent for the 5- and 10-deg elevation angles, respectively.

The percent cumulative probability that a given number of satellites will be observed simultaneously as a function of user latitude for all user longitude positions is shown in Figure 34. The distribution indicates that satellite visibility at higher latitudes is better than at other latitudes, and that at higher elevation angles the probability of a high number of satellite sightings is reduced at all latitudes.

The orbital parameters of the Phase III deployment used here are listed in Table XIV. These data along with the resultant Phase III satellite coverage and GDOP data are taken from Reference 12. All GDOP data is based on a minimum GPS user elevation angle of 5°.

7.4.2 PHASE III GDOP'S

With at least six satellites always in view at any point on the earth, User location and time synchronization during Phase III will depend on GPS UERE only (no altimeter input), and will be about an order of magnitude better than Phase II results. In replacing the altimeter, the effects of UERE on the vertical dimension will be accounted for in this section by introduction of another parameter called VDOP. Similar to previous treatments, the vertical error is the product of UERE and VDOP.

Figure 35 indicates the cumulative probabilities of these three GDOP factors for all time-space, assuming a 5° elevation angle. The exact latitude dependence is indicated in Figures 36 through 38. Based on these data, and the UERE derived in Section 7.1, the worst-case (99 percentile) horizontal, vertical, and time synchronization 1σ errors are expected to be 58 feet, 98 feet, and 55 nsec respectively, for the Aerosat application.

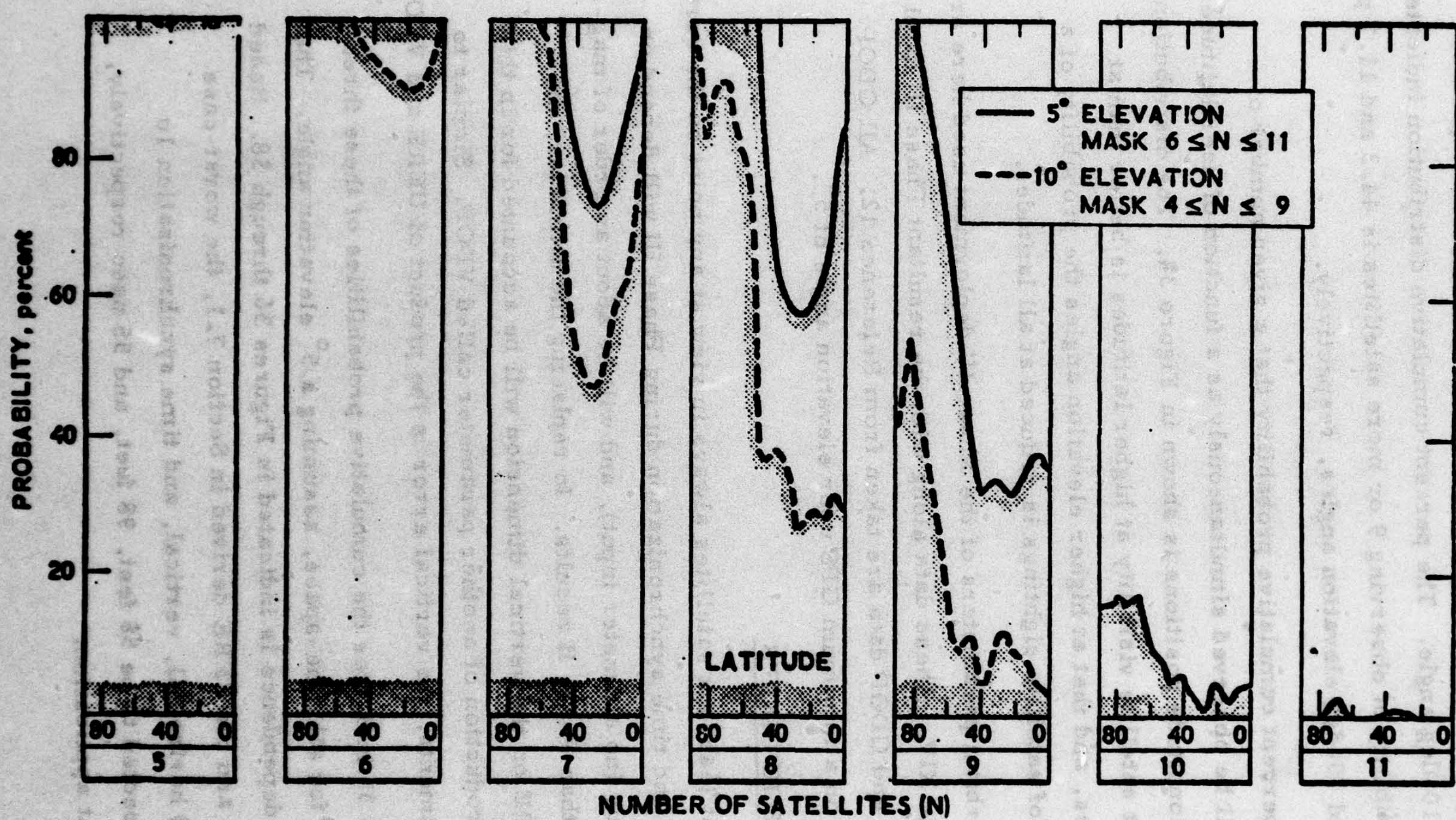

FIGURE 34. GPS PHASE III - PROBABILITY DISTRIBUTION OF GLOBAL SATELLITE VISIBILITY

Table XIV. GPS Phase III - 3 x 8 Nominal Orbit Parameters

SAT. No.	ECCENTRICITY	ARGUMENT OF PERIGEE (deg)	RA OF AN (deg)	INCLINATION (deg)	MEAN ANOMALY (deg)	PERIOD (hrs)
1	0.00	0.00	0.00	63.00	-15.00	12.00
2	0.00	0.00	0.00	63.00	30.00	12.00
3	0.00	0.00	0.00	63.00	75.00	12.00
4	0.00	0.00	0.00	63.00	120.00	12.00
5	0.00	0.00	0.00	63.00	165.00	12.00
6	0.00	0.00	0.00	63.00	210.00	12.00
7	0.00	0.00	0.00	63.00	255.00	12.00
8	0.00	0.00	0.00	63.00	300.00	12.00
9	0.00	0.00	120.00	63.00	15.00	12.00
10	0.00	0.00	120.00	63.00	60.00	12.00
11	0.00	0.00	120.00	63.00	105.00	12.00
12	0.00	0.00	120.00	63.00	150.00	12.00
13	0.00	0.00	120.00	63.00	195.00	12.00
14	0.00	0.00	120.00	63.00	240.00	12.00
15	0.00	0.00	120.00	63.00	285.00	12.00
16	0.00	0.00	120.00	63.00	330.00	12.00
17	0.00	0.00	240.00	63.00	0.00	12.00
18	0.00	0.00	240.00	63.00	45.00	12.00
19	0.00	0.00	240.00	63.00	90.00	12.00
20	0.00	0.00	240.00	63.00	135.00	12.00
21	0.00	0.00	240.00	63.00	180.00	12.00
22	0.00	0.00	240.00	63.00	225.00	12.00
23	0.00	0.00	240.00	63.00	270.00	12.00
24	0.00	0.00	240.00	63.00	315.00	12.00

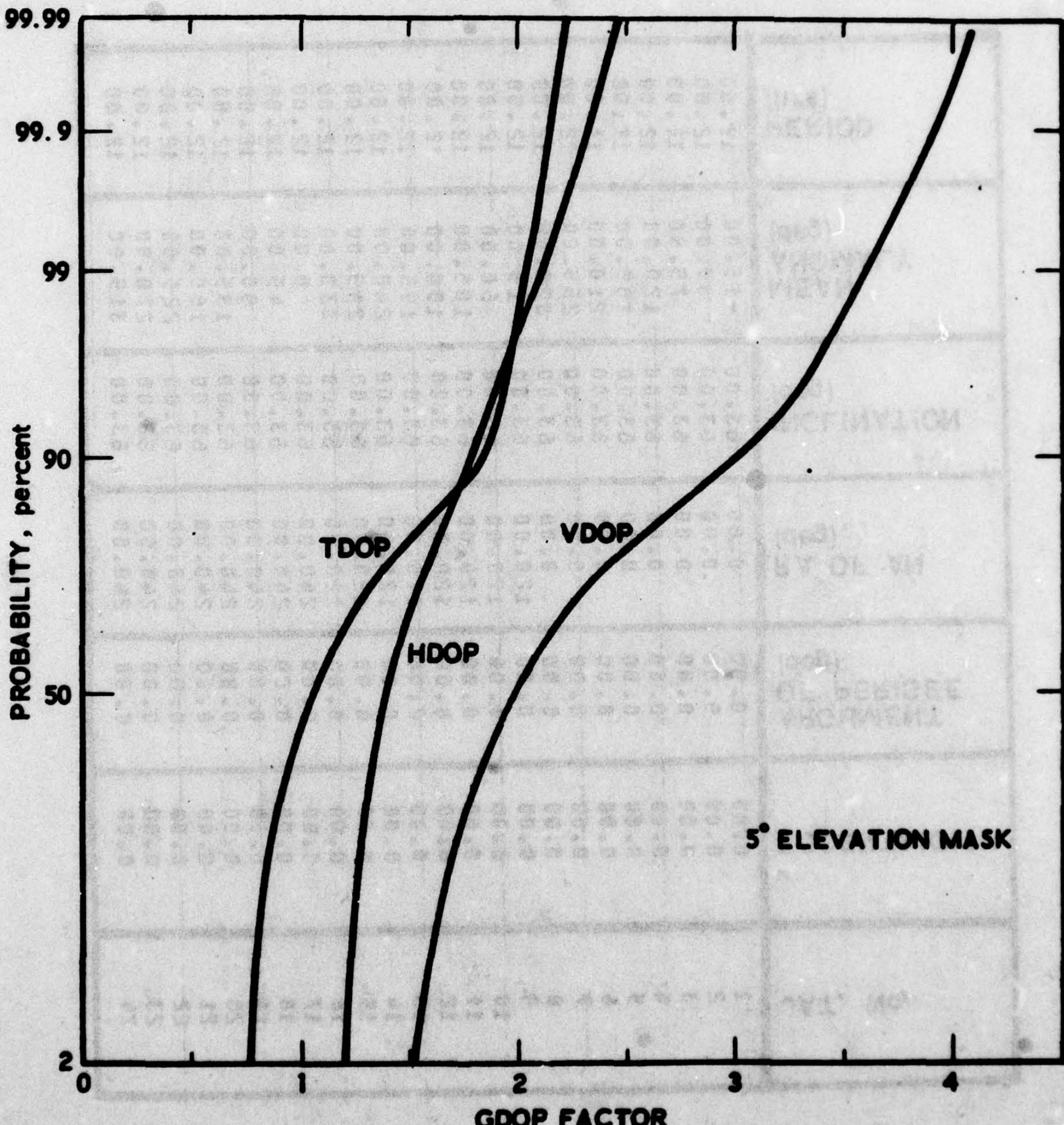

Figure 35. GPS Phase III Global Geometric Performance

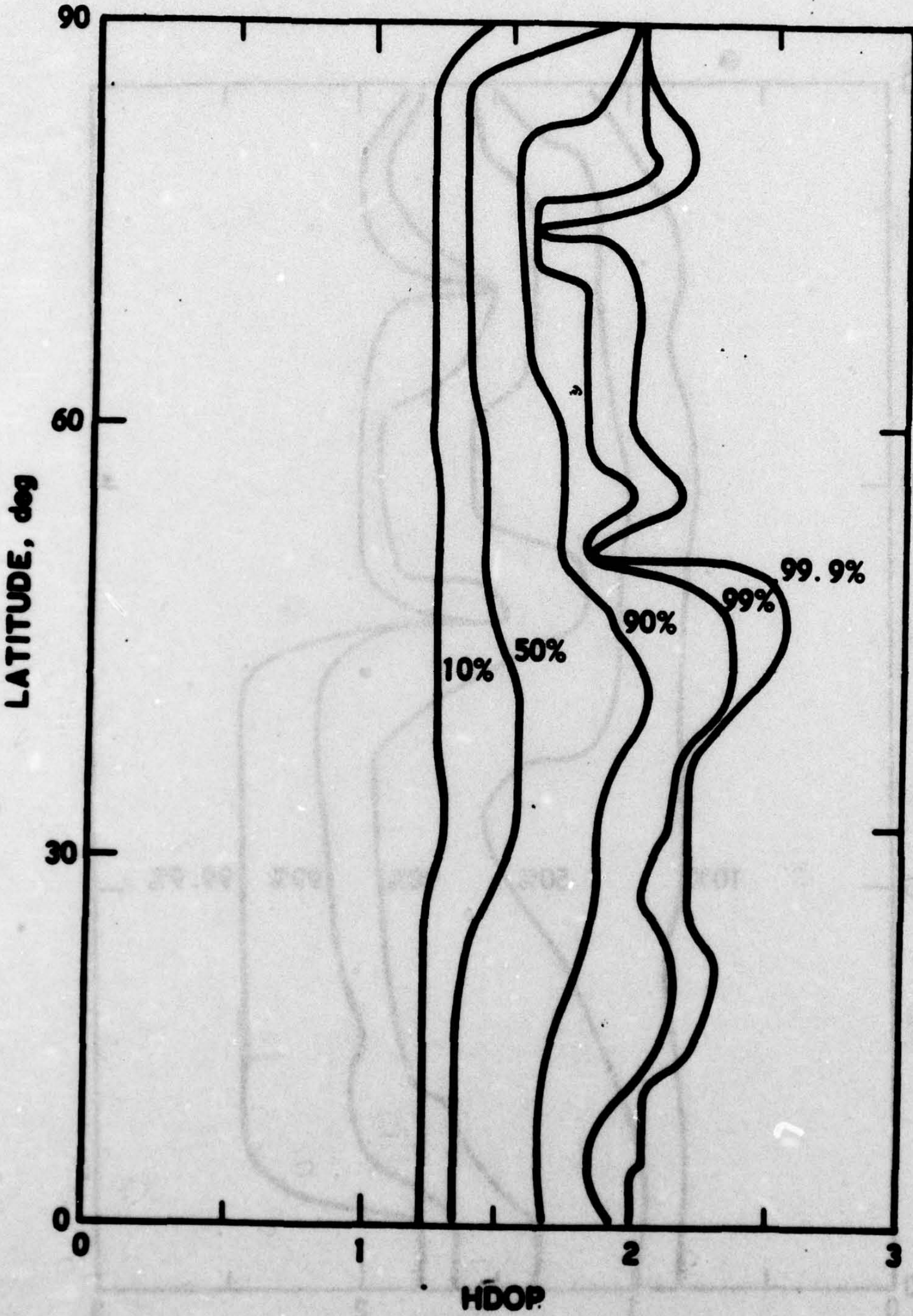

Figure 36. GPS Phase III HDOP Performance

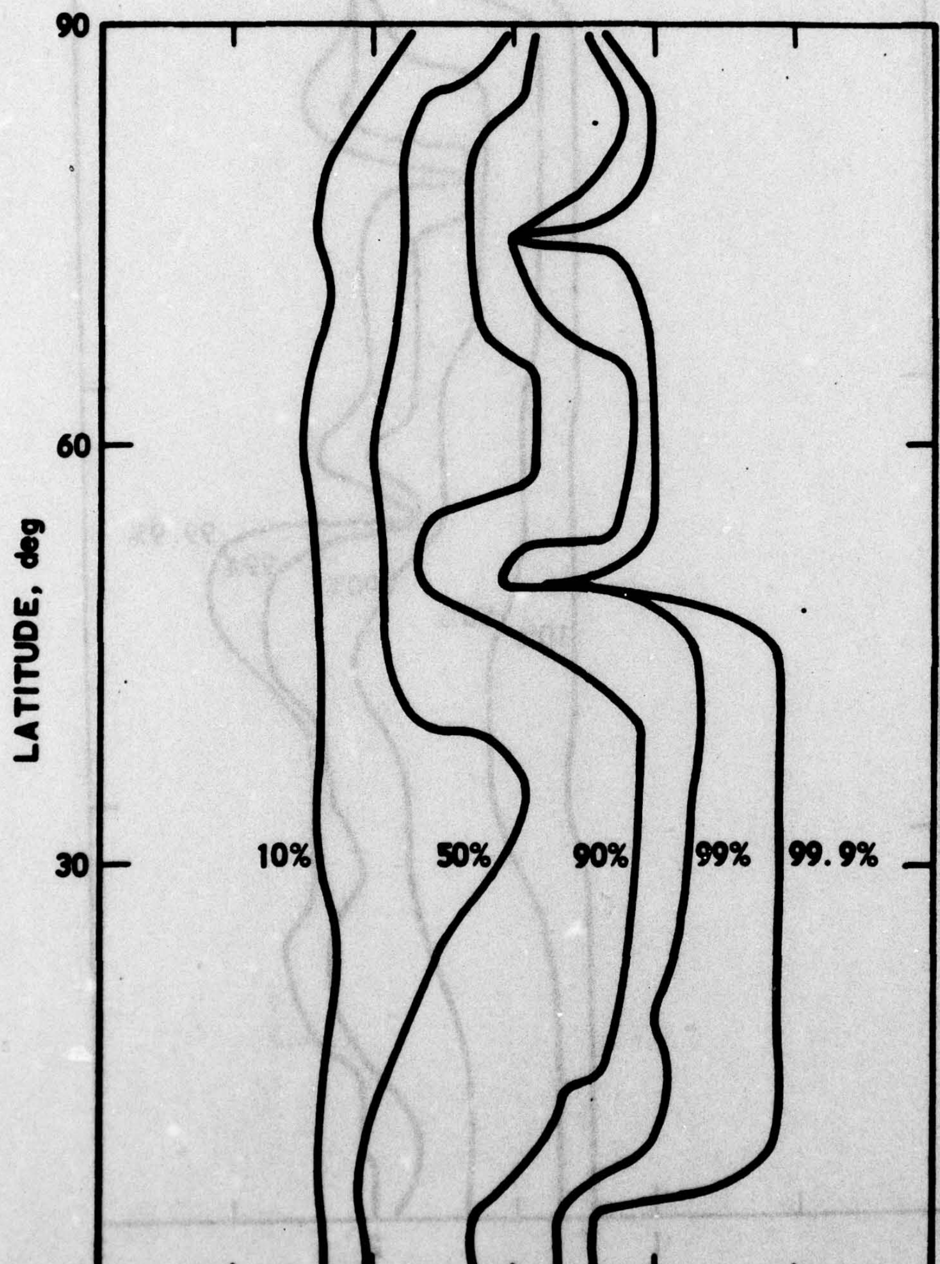

Figure 37. GPS Phase III TDOP Performance

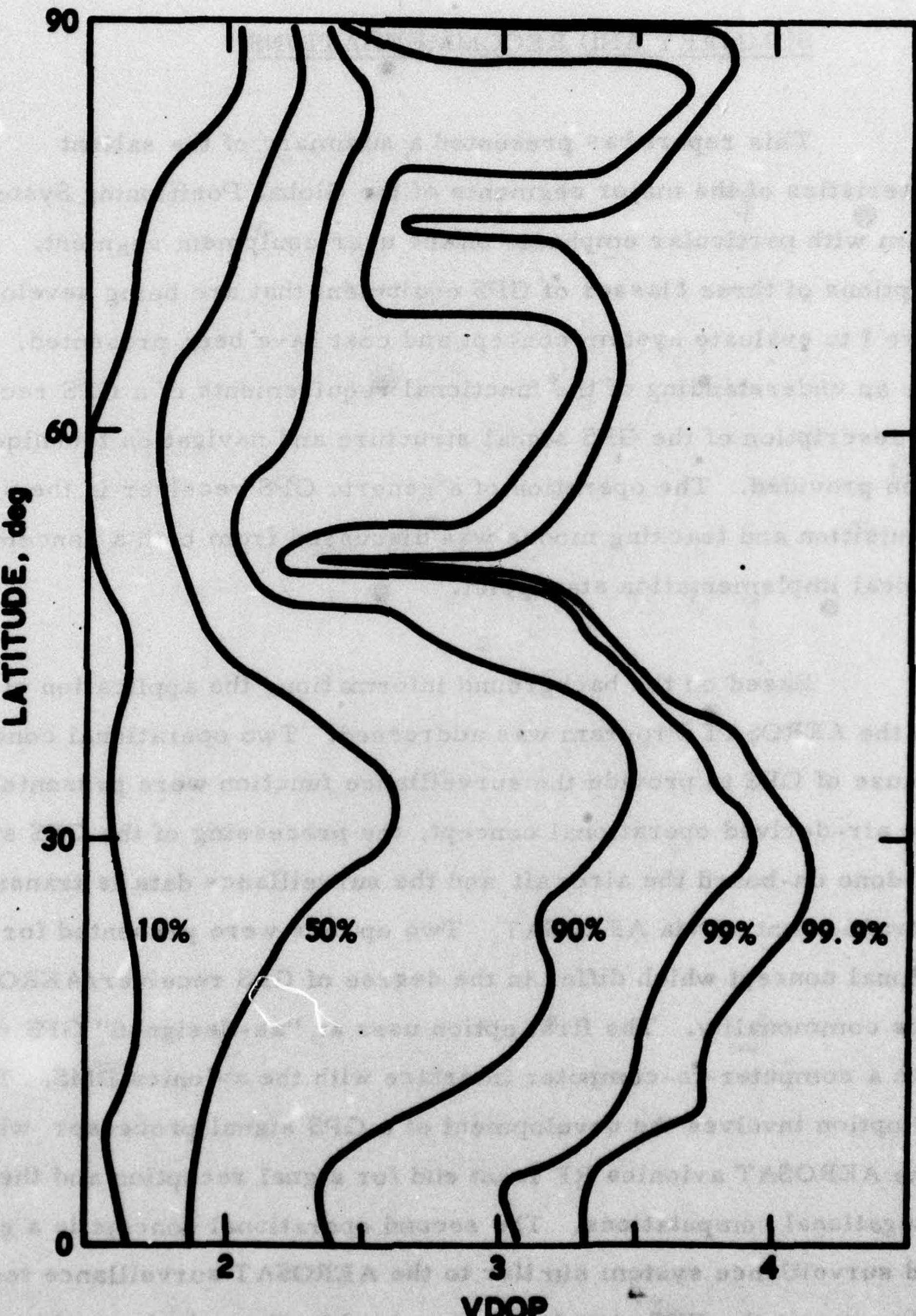

Figure 38. GPS Phase III VDOP Performance

8. SUMMARY AND RECOMMENDATIONS

This report has presented a summary of the salient characteristics of the major segments of the Global Positioning System Program with particular emphasis on the user equipment segment. Descriptions of three classes of GPS equipment that are being developed in Phase I to evaluate system concept and cost have been presented. To provide an understanding of the functional requirements of a GPS receiver, a description of the GPS signal structure and navigation technique has been provided. The operation of a generic GPS receiver in the signal acquisition and tracking modes was discussed from both a conceptual and typical implementation standpoint.

Based on the background information, the application of GPS to the AEROSAT Program was addressed. Two operational concepts for the use of GPS to provide the surveillance function were presented. For the air-derived operational concept, the processing of the GPS signals is done on-board the aircraft and the surveillance data is transmitted to air traffic control via AEROSAT. Two options were presented for this operational concept which differ in the degree of GPS receiver/AEROSAT avionics commonality. The first option uses an "as-designed" GPS receiver with a computer-to-computer interface with the avionics DMS. The second option involves the development of a GPS signal processor which uses the AEROSAT avionics RF front end for signal reception and the DMS for navigational computations. The second operational concept is a ground-derived surveillance system similar to the AEROSAT surveillance technique. For this concept the GPS signals are received by the avionics and transponded unprocessed via AEROSAT to the ASET/ASCC where signal processing is performed.

The impact of these three options on the AEROSAT Test and Evaluation Program and an operational AEROSAT system was assessed. Option 1 (use of "as-designed" GPS receiver) results in the minimum impact to the AEROSAT T&E avionics since the two systems operate independently with only a computer-to-computer interface required. However, this option represents the maximum avionics cost for an operational AEROSAT system, since two RF front ends and two general purpose computers are required for the combined system. Option 2 (development of a GPS processor) explores the possibility of using a common RF front end and computer for both systems. For this option the design of the AEROSAT L-band avionics RF front end must be sufficiently broadband to receive both GPS and AEROSAT signals. In addition, since the AEROSAT forward L-band and GPS signals are cross-polarized relative to each other, several techniques for receiving both signals were described. All of these techniques require the use of two antennas. The alternative is to change the polarization of the AEROSAT L-band forward link to be compatible with GPS. Option 3 (GPS signal turnaround) has similar requirements with regard to the AEROSAT RF front end. In addition, Option 3 requires a substantial improvement in avionics performance. The AEROSAT reference avionics do not provide sufficient link quality for GPS receiver operation. An increase of approximately 6 dB in avionics G/T and EIRP are required for Option 3 to be feasible. Due to the major impact on avionics design and system performance limitations, Option 3 was not considered further for evaluation during the AEROSAT T&E Program.

The position determination performance of GPS is a function of satellite location errors, satellite-to-user range measurement errors including both receiver measurement and propagation errors, and satellite /

user geometry. The performance of the system is characterized by User Equivalent Ranging Error (UERE) which combines all system range measurement errors, and Geometrical Dilution of Precision (GDOP) which is a measure of the satellite/user geometry effects. Each of the error sources which constitute UERE were discussed and estimated. For those errors which depend on receiver implementation, a generic GPS receiver which uses only the C/A code on L_1 was assumed. For the AEROSAT application, the UERE is estimated to be 25 feet (1σ) for a received C/N_o of 35 dB-Hz. Since the AEROSAT Program spans both Phase II and III of the GPS program, GDOP performance for both phases was presented. For the Phase II configuration, three satellites are visible approximately 58% of the time on the average in the area of interest in the Atlantic. With three satellites available the use of altimeter data is required. The effects of satellite/user geometry on horizontal location accuracy are described by two Horizontal Dilution of Precision (HDOP) factors, $HDOP_A$ and $HDOP_R$, which apply to altimeter and ranging errors, respectively. Approximately 50% of the time, when 3 or more satellites are visible, $HDOP_A$ is in the less than 2.4 and $HDOP_R$ is less than 6. Since altimeter errors are on the order of several hundred feet while ranging errors are approximately 25 feet, altimeter errors will dominate the horizontal location accuracy for the Phase II configuration. For an altimeter error of 300 feet and a ranging error of 25 feet, the resulting horizontal accuracy will be less than 750 feet (230 meters), 1σ. The AEROSAT surveillance system results in errors which range from several hundred meters to several thousand meters for aircraft close to the equator. The Phase III GPS configuration provides better coverage and GDOP performance. For this configuration a minimum of four satellites are visible on a worldwide basis for a 5 degree minimum elevation angle, so that altimeter data is not required. The Phase III system results in HDOP values less than approximately 2.5, 99.9% of the time for all latitudes. Vertical Dilution of Precision (VDOP) factors are less than approximately

4, 99.9% of the time for all latitudes. Assuming a UERE of 25 feet, the Phase III configuration results in 1 σ errors better than 20 meters and 30 meters in the horizontal plane and vertical directions, respectively, 99.9% of the time for all latitudes.

The use of GPS to provide surveillance data results in a significant cost saving for an operational AEROSAT system. The AEROSAT surveillance technique requires a minimum of two satellites, and, for an operational system three satellites may be required to back-up the surveillance function in case of a satellite failure. An operational AEROSAT system which uses GPS to provide the surveillance function requires only two satellites; one operational and one back-up. Since the cost of building and launching an AEROSAT exceeds $25 M, the cost saving for such a system are substantial. In addition, GPS provides better coverage and performance for surveillance than currently envisioned for the AEROSAT surveillance technique.

The cost savings and performance potential offered by GPS to an operational AEROSAT system warrent the evaluation of GPS during the AEROSAT test program. Since the two operational concepts for use of GPS in the AEROSAT program represent different surveillance philosophies, both concepts should be tested and evaluated. The cost and performance advantages of using GPS are applicable to both concepts. Testing and evaluation of both concepts will allow the determination of the surveillance philosophy which is more desirable for an operational system. Specific comments and recommendations on the three options which represent these concepts are presented below.

It is recommended that, as minimum, Option 1 (use of "as-designed" GPS receiver) be implemented in the AEROSAT T&E Program. The option will provide operational experience with GPS with minimum

modification of the AEROSAT L-band avionics design. The types of GPS receivers that will be available for Phase II and III time frames is unknown at this time and depends on the results of Phase I testing. However, it is assumed that a receiver similar to the Z-class user equipment will be available and should be adequate for oceanic surveillance operations. The Z-set user equipment operates on the C/A code on L_1 and processes four GPS signals sequentially. For Phase I, 14 Z-sets are being produced at a recurring cost per set goal of $25K. Discussions with Magnavox indicate that the recurring production cost per set is estimated to be $15K in lots greater than 100. The Z-set includes antenna assembly, receiver, and data processor.

Option 2 requires the modification of the AEROSAT avionics and the development of a GPS processor. The design of the AEROSAT avionics RF front end must be made compatible with the GPS signals. Depending on the avionics design this may compromise the performance of both the AEROSAT and GPS systems. This is primarily due to the polarization differences between AEROSAT and GPS signals which could be changed for an operational system. In addition, this option requires a portion of the DMS and some software development. A cost/benefit analysis has not been performed to ascertain the advantages of using a common RF front end and computer for both systems. If the predictions of $15K per unit for the Z-class set are realized, the savings due to equipment commonality may not be appreciable. For the relatively small number of oceanic aircraft this option may not be cost effective especially in view of the GPS processor hardware and software development costs. If this option is to be pursued, the decision should be made promptly in order to influence avionics design and begin development of the GPS signal processor.

The Global Positioning System represents a resource which may be used by the FAA to provide the surveillance function for oceanic air traffic control in a cost effective manner. The evaluation of GPS as a part of the AEROSAT T&E Program will provide operational experience and data which may be used to assess the role of GPS in an operational AEROSAT system.

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